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VOLUME LIII NUMBER 4

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

EDITED BY

GEORGE E. HALE
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MAY 1921

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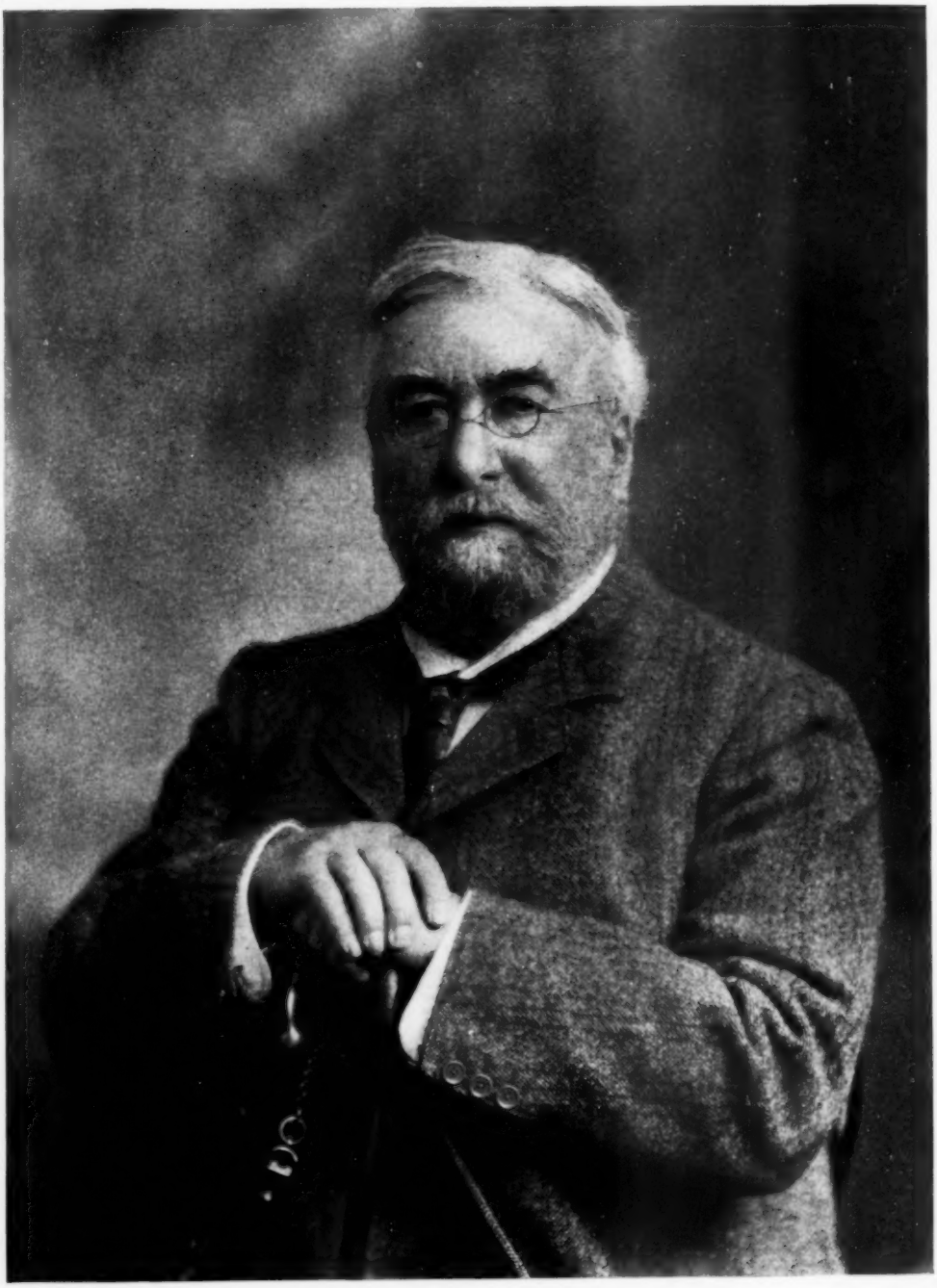

SIR NORMAN LOCKYER
From a photograph taken in 1903

THE
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SIR NORMAN LOCKYER, 1836–1920

By A. L. CORTIE, S.J.

Among the names of those who laid the foundations of that branch of astronomical science, which dealing mainly with the constitution of the heavenly bodies is known as astrophysics, a prominent place will always be held by that of Norman Lockyer. He was one of the pioneers in the application of the spectroscope to the study of the solar surface and envelopes, and in the detailed examination of the spectra of the stars. He made fundamental discoveries, especially in solar physics, and he developed modes and methods of research which have subsisted even to the present day. The enunciation by Kirchhoff in 1859, of the principle underlying the reversal of the Fraunhofer rays in the solar spectrum, was an opportunity and an incentive to discovery offered to all astronomers. Lockyer was one of the very few to appreciate what a vast field lay open in the domain of the physics of the heavenly bodies, and with enthusiasm and energy, with native skill and great courage, he entered into his labors. We must not forget that before he was subsidized by the government, and established as an official astronomer, Lockyer was an amateur, and as such a worthy representative of the long line of amateur astronomers who, especially in England, have done yeoman service in the advance of the science. He took to astronomy because he loved it, and because of the appeal it made to his intellectual faculties. It was in his leisure hours, when freed from the daily toil which was his lot as a

secretary in the war office, that Lockyer helped to lay the solid foundations of the science of astrophysics.

He was born at Rugby May 17, 1836, and died at the Hill Observatory, Sidmouth, August 17, 1920. He had therefore completed his eighty-fourth year. Janssen, whose name will ever be associated in the history of astrophysical science with that of Lockyer, died in 1907, and was in his eighty-fourth year. Lockyer received his first lessons in science from his father, who was one of the early workers in research with regard to the electric telegraph. He was educated at various private schools and on the Continent. This was fortunate, for had he been educated at any of the public schools, or universities, he would have been taught very little, if any, science, and had he taken up the career of an astronomer, he would doubtless have been absorbed in the rank and file of those who followed the traditional, and in those days somewhat narrow, grooves. But he possessed independence of mind, resourcefulness, adaptability, and moreover, as an amateur, was at liberty to select his own field for work. In the year 1857 he received an appointment as a clerk in the war office, and his work there was so much appreciated that in 1865 he was selected to edit the Army Regulations. In 1870 he was made secretary of the Duke of Devonshire's Royal Commission on Science. This important post he owed not only to his proved business capacity but also to the fame which he had already acquired by his great discovery of the year 1868. When this Commission had finished its labors, he was transferred to the Science and Art Department, and became definitely an official astronomer, or rather a government servant devoted to research in the domain of astrophysics. But only partially, for his official duties still included the organization of the loan collection of scientific apparatus and of the Science Museum, which was subsequently founded, as well as the inspection of training colleges.

In 1862 Lockyer was living at Wimbledon and had erected, in a garden in front of his house, a $6\frac{1}{4}$-inch equatorial by Cooke of York. With this instrument he observed the opposition of Mars of that year, and communicated an account of his observations, which seems to have been his first scientific paper, to the Royal Astronomical Society.

He was first interested in the sun by the warm controversy as to the nature of the constituents of the solar surface which Secchi and Langley rightly described as granular, but which Nasmyth had likened to willow leaves. Lockyer took part in the discussion and contributed a paper on the subject to the Royal Astronomical Society. He noticed in particular the changing forms of these elemental constituents of the solar photosphere.

Similarly, it was the publication of Faye's theory of sun-spots in the year 1865 which suggested to Lockyer that the question as to the nature of sun-spots could best be solved by the application of the spectroscope. Accordingly he purchased a direct-vision Herschel-Browning spectroscope of small dispersion, and attaching it to his equatorial threw the image of a spot on the slit. The absorption lines visible in the spectrum of the photosphere were present in that of the spot, but in some cases were widened in the spot. It followed therefore that a sun-spot was seemingly a region of increased absorption.

These preliminary spectroscopic observations of the sun-spots whetted the appetite of Lockyer to explore the solar envelopes, and in particular to determine the precise nature of the solar flames photographed by De la Rue and Secchi in the total solar eclipse of 1860. In this important matter in the history of solar spectroscopy it will be better to quote Lockyer's own words as set forth in a "Memorandum on the Solar Researches Carried on by Sir Norman Lockyer 1863–1906," which was privately printed in London, 1906. He writes:

> Talking these matters over with Balfour Stewart, we came to the conclusion that it could help us in other ways, because, if the objects photographed by De la Rue in 1860 were gases or vapors, their bright lines ought to be revealed when a large dispersion was used, although I had failed to trace them with a small one. . . . . As great dispersion was required both for the spectra of the "red flames," and for settling the question raised by the widening of lines in spots, when my paper of 1866 was sent in to the Royal Society, I made my first application to the Government Grant Committee for money to provide a solar spectroscope of large dispersion to attach to the equatorial. The grant was approved; but, in consequence of delays, the instrument did not reach me till October, 1868, by which time I had changed my residence from Wimbledon to 24 Fairfax Road, West Hampstead, where I had built an observatory, the 6¼-inch Cooke being still the instrument used.

> On October 20, 1868, I saw the bright lines, as I had anticipated in 1866. On November 5 I discovered that the prominences were but higher waves in a sea which enveloped the photosphere. This new envelope I named the chromosphere.

But Lockyer had been anticipated in the observation of the bright lines of the chromosphere and prominences, independently, and unknown at the time, by Janssen, who had observed the bright-line spectrum of the prominences in the total solar eclipse of August 18 at Guntoor, in India. So vivid were these lines that they had forced Janssen to exclaim, "Je verrai ces lignes-là en dehors des éclipses!" Next day and for several days he carried out his intention and succeeded, as he had intuitively anticipated, in viewing the bright hydrogen and helium lines even on the uneclipsed sun. Janssen sent a communication on the subject to the Academy of Sciences in Paris. By a dramatic coincidence it arrived in time to be read at the same session, on October 26, as Lockyer's account of his success in viewing the spectrum of the prominences, which had also been sent to the Academy. The two names are indissolubly united in this discovery of prime importance in solar physics. The Academy of Sciences to commemorate the discovery caused a medal to be struck which bears the effigies both of Janssen and of Lockyer.

In the dedication of the papers collected together in his work *Solar Physics* Lockyer wrote:

> This book is dedicated to Balfour Stewart and to Jules Janssen. Encouraged by the first of these friends, I have undertaken the researches which have gained me the friendship of the second.

There is no sign here of petty jealousy, or of stupid claims of priority. In the year 1870, when Paris was besieged by the Germans, Lockyer by his kindly intervention obtained a safe conduct for his friend, so that he might be able to observe the total solar eclipse of that year. But Janssen spurned the idea of receiving any favors from the enemies of his country, and preferred to leave the beleaguered city in a balloon. Those of us who attended the meetings of the International Union for Co-operation in Solar Research at Meudon, in 1907, will remember the large painting of this episode which was hung in the room in which we gathered for our discussions.

This important discovery created great enthusiasm among astronomers, and undoubtedly promoted throughout the whole world the foundation of observatories devoted especially to solar research. Lockyer was quick to perceive that, in order to ascertain the origin and character of the bright lines he had observed in the prominences, it would be necessary to compare the celestial with terrestrial sources of light. He was fortunate in obtaining the co-operation of Professor Frankland, and together they made experiments upon hydrogen, sodium, iodine, under various conditions of pressure and of temperature. He soon recognized as the results of these experiments that the yellow line in the chromosphere and prominences could not be due to hydrogen or to sodium. It therefore represented an unknown element which he named "helium." It was not until twenty-seven years later that Sir William Ramsay detected helium in the mineral cleveite and in some of the gases which are given off from terrestrial waters. We also know now that it is an emanation from radium, and it plays a most important part in all questions concerning the constitution of matter.

Lockyer's activities at this period were also directed to the observation of total solar eclipses in Sicily in 1870, and in India in 1871. On the first occasion he was balked by clouds, but in 1871 he was successful and, with Respighi, employed for the first time in eclipses the prismatic camera, an instrument which had been so successful in the hands of Secchi in furnishing the various types of stellar spectra. Although the prismatic camera does not give the exact wave-length of the lines of the chromospheric spectrum, for this purpose a slit spectroscope and a reference spectrum is needed, yet it has the advantage of showing spectral images of the radiations as bright arcs, the extent of the arc in angle being a function of the height to which the metallic vapor ascends in the sun's atmosphere. It was certainly a brilliant idea to adopt the instrument for studying the bright lines in total solar eclipses.

Lockyer may also be credited with being the first to realize the necessity of combining laboratory researches with the observation of the spectra of the heavenly bodies. By the year 1872

he had accumulated a considerable number of observations of the lines in the chromosphere. He had also, by his studies of the hydrogen spectrum with Frankland, come to the conclusion that the arrow-head appearance of the F line in the chromosphere was due to pressure. He would therefore undertake a research on the spectra of the metallic elements under varying conditions of temperature and of pressure. Accordingly, aided by a government grant, he set up a laboratory in his private house and engaged the services of an assistant. In the year 1873 his instruments, astronomical and physical, were moved to South Kensington and erected in temporary wood and canvas observatories in the garden of the Royal Horticultural Society. A sapper, when not otherwise engaged, was told off as his photographic assistant. Here we have the prototype and the germ idea, which has fructified in such a magnificent modern astrophysical observatory as that of Mount Wilson.

Lockyer had been elected a Fellow of the Royal Society in the year 1869, and his contributions to its *Proceedings* and *Transactions* on his researches in spectrum analysis in connection with the sun were numerous, original, and important. In his photographs of the metallic spectra he had detected the difference between long and short lines, the thickening and thinning of lines with pressure, the variation in length, brightness, strength, and number of lines, and the change in general produced by variations in temperature. He had made a photographic map of the solar spectrum between wave-lengths 3900 and 4100 on a scale four times that of Angstrom's map, and had plotted on it the comparison with lines of iron, calcium, magnesium, nickel, and other elements. Meanwhile he had continued his systematic observation of the solar prominences, employing a seeing-slit, had discovered the metalloids carbon and silicon in the sun, and had been the first to recognize that the displacements of the spectral rays in the spectrum of the prominences were due to radial movements in the gases. This he rightly attributed to the Doppler-Fizeau principle, which was then little known. He was the first also in showing that the coronal ring at the wave-length 5303, then known as K 1474, from the position

it occupied in Kirchhoff's maps, was coterminous with the lower corona. His photographs also gave detailed knowledge of the spectrum of the lowest layers of the solar atmosphere, the so-called "flash" spectrum, which is only visible in the first two and last two seconds of totality in total solar eclipses.

It was not until the year 1879 that a Solar Physics Observatory was definitely established at South Kensington, and a committee appointed "to advise on the methods of carrying on observations on solar physics." Lockyer was of course the dominating personality of this committee, and was practically free to carry on any researches he considered to be advisable. The next year he was directed to give a course of lectures on astronomical physics to the students of the science school, and in 1882 was appointed full professor. In this capacity he inaugurated a course of practical training in the use of instruments, which eventuated in the increase of his observatory staff by the inclusion of research students. Thus Professor Fowler joined the staff in this capacity in 1885, and became Lockyer's demonstrator in 1888. The grant in aid at this time was £500 annually, which was increased in 1898 to £1,000.

It is wonderful what Lockyer effected on such an inadequate pittance. But he had inspired his staff with some of his own enthusiasm and spirit of hard work, and a series of memoirs appeared under the auspices of the Solar Physics Committee which are indispensable to all workers in astrophysics, and are models of accurate research. One of the most important of these researches was that which was concerned with the differences in the radiations given by an element according to its vaporization by the flame, the electric arc, or the electric spark. In particular he drew the important distinction between the lines which appear in the arc alone and those which are strengthened in passing from the excitation of the arc to that of the spark. The latter lines he named "enhanced" lines, and their importance in all questions of solar and stellar physics is paramount. They are for instance the characteristic lines of the "flash" and chromospheric spectra, and are prominent in the early spectral phases of new stars.

As we have seen, Lockyer's very first observations of the solar surface with the spectroscope were those of sun-spots. At South Kensington a very long series of observations, extending over many years, were undertaken under his direction on not the widest but the six most widened lines in each of the regions F–*b* and *b*–D. From the reduction of these observations he found that the lines widened in sun-spots were not common to spots and prominences, and that lines of the prominence, at least those produced in the lower strata, were precisely those which are intensified in passing from the arc to the spark. Lockyer also announced that the lines most affected in sun-spots at the times of solar maxima were the fainter lines, while those similarly most prominent at solar minima were the stronger lines. He connected this periodic variation with the prevalence of the monsoons in the Indian Ocean, and consequently with the years of plenty and of famine. But about the same time (1881) we at Stonyhurst, as a supplement to these investigations, took up the systematic observation of the most widened lines, and of all the lines in the region C–D. It was very soon evident that the sun-spot spectrum was constant, with practically no variation, though there was some evidence of stronger iron lines being found among the most widened lines at times of sun-spot minimum. In their later publications on this subject the South Kensington observers adopted the same view, and more than thirty years' observations have convinced me that the sun-spot spectrum is essentially constant. The great predominance of the fainter lines of the elements among the most widened lines, and especially of those of titanium and vanadium, were concomitantly and independently observed both at South Kensington and at Stonyhurst. Such observations were preliminary to the magnificent map of the sun-spot spectrum produced by Hale at Mount Wilson, and to the solution of the appearance of widening as due to the magnetic fields of sun-spots, as also to Fowler's identification of the spot-bands as being due to titanium oxide. With regard to sun-spots also, the areas of all such, in the period 1832–1900, from all available sources, were utilized to form curves, which were issued as one of the publications from South Kensington.

Lockyer directed no less than eight expeditions to observe total eclipses of the sun. In fact so predominant was his influence and strong personality in these expeditions that one of his friends, we think it was Clerk-Maxwell, good-naturedly lampooned him in the following humorous couplets:

> And Lockyer, and Lockyer,
> Gets cockier, and cockier;
>
> For he thinks he's the owner
> Of the solar corona.

In several of those which occurred in distant regions he had the service of a war vessel and its crew placed at his disposal by the Admiralty. He had unbounded faith, and rightly so, as we have ourselves experienced, in the adaptability and proverbial readiness of the "handy man." Accordingly he would train quite a number of officers and men to take part, under himself and his immediate assistants, not only in the astronomical observations, but in all sorts of incidental meteorological and kindred observations. He united enthusiasm with great orderliness and method. Each time he took part in an eclipse expedition he made the previous observations serve as the foundation of further researches. With the prismatic camera, for instance, he felt his way, and increased the dispersion at each succeeding eclipse. He has produced a series of most valuable memoirs of his observations, especially noteworthy being the chromospheric reductions in the Indian eclipse of 1898, when he had Fowler as his assistant. He also obtained important results of permanent value on the varying forms and on the constituents of the sun's corona.

Although observation and experiment are the sure basis and foundation of natural science, yet its chief end and function is the search for the causes of phenomena. Hence we find in the progress of all science that working hypotheses are broached which strive to co-ordinate all the knowledge so far acquired and to point the way to fresh observation and experiment. Most of these are discarded as scientific knowledge advances to be replaced by others of more far-reaching import. But not wholly discarded, for in a good hypothesis many of the root or germ ideas survive.

The various changes noticed in the spectra of the elements under varying conditions of temperature, pressure, and electrical excitation, in experiments in the laboratory, had suggested to him the idea that either the high temperatures, or the electric stresses employed, were breaking up the substances into various "molecular groupings." With regard to the sun, the hypothesis enunciated supposed that, at the high temperatures prevailing in the photosphere and the lower reaches of the overlying envelopes, the chemical elements were broken up or dissociated. Accordingly, if the elements as known to us exist at all in the sun, they are found only in the higher or relatively cooler layers of its atmosphere. Vertical currents bring down the formed material to be dissociated in the lower reaches. Hence reduced in density it reascends to become formed material again in the appropriate heat level. The hypothesis is worked out fully in his work on *The Chemistry of the Sun*. The fundamental idea, that of dissociation of the chemical elements, subsists, whatever may be thought of the details of his scheme, and at present in the electronic theory as to the constitution of the elements is of very great importance.

In his studies in solar physics Lockyer was naturally led to investigate the connections which may possibly exist between solar and terrestrial phenomena. As early as 1872 he published a paper on the relation between sun-spots and meteorology in which he endeavored to show that a relation exists between the sun-spots and the cycle of monsoons. Thirty years later, in conjunction with his son, Major J. W. S. Lockyer, he returned to the same subject. Having detected in the solar prominences a period of about 3.8 years, he showed that this period coincided with a similar periodic intensification of both high- and low-pressure means for India and Cordoba, and that pressure changes respond more quickly to solar influence than does rainfall. He next extended the investigation to the Pacific Archipelago and to Australia, and showed that the connection was substantiated. A corresponding area in America gave inverse action like Cordoba. Finally, these short-period variations of atmospheric pressure, which he assimilated to the Bombay-Cordoba "seesaw," appeared to be prevalent at numerous stations scattered all over the world.

If this oscillation of terrestrial pressure types can be connected with periodicity in the prominences, a means is afforded of long-period weather forecasting. Certainly the general law of the circulation of winds in the Southern Hemisphere, which was established by the Lockyers in this series of memoirs, has been verified, and is now admitted by many meteorologists.

Concomitantly with these researches, the solar prominence and spot circulation for the period 1872–1901 was studied by father and son. It was established that the prominences show a poleward drift, that at prominence minima there is only one zone, in contradistinction to the sun-spots which affect two zones, though the subsidiary maxima were coincident in time with two zones of prominences. This led them to investigate the relation between solar prominences and terrestrial magnetism. It was found that polar prominences follow a different law from equatorial prominences, and that while diurnal magnetic variations seemed to be in agreement with the equatorial prominences, great magnetic storms vary with polar prominences. The seasonal variation in the frequency of magnetic storms, the minima occurring near the equinoxes, was attributed to the position of the sun's axis relatively to the earth. But we think that in so far as metallic prominences are connected with sun-spots, it is only incidentally that prominences are associated with magnetic disturbance. Otherwise there does not seem to be any link between the two phenomena. It is quite true, however, that magnetic disturbances are more frequent when the heliocentric position of the earth is in the semi-equatorial solar regions.

It was not until the year 1890 that Sir Norman Lockyer extended his researches so as to include observations of the spectra of nebulae and stars. He began with the spectrum of the nebula in Orion, of which, with a two-prism spectroscope attached to the 30-inch reflector, he obtained a photograph showing twenty-eight, and later over forty, lines, some of which he noted as coincident with the chief bright lines in the star P Cygni. Comet *a* (1890) and Nova Aurigae (1892) next attracted his attention, and in the latter year he published a discussion of 443 photographs of the spectra of 171 stars taken chiefly with a 6-inch prismatic camera, furnished

with objective prisms of $7\frac{1}{2}^\circ$ and 45° angle. The paper contained a classification of the stars based on the extent of the absorption in the ultra-violet. It is noteworthy from the fact that he divided the stars, on a temperature basis, into two main groups of ascending and descending stars. It will not be necessary to discuss in detail his observations of the spectra of other stars, as β Lyrae, γ Cassiopeiae, α Aquilae, Nova Persei, in which he had the expert assistance of Professor Fowler and Mr. F. E. Baxandall. Several of the memoirs issued under the auspices of the Solar Physics Committee contain most valuable detailed lists of lines observed in the spectra of stars, and, what is most valuable, corresponding lists of the chemical origins of the lines. In particular we may mention the catalogue of four hundred and seventy of the brighter stars classified according to their chemistry, the memoir on some of the phenomena of new stars, and, as an associated laboratory research, the tables of wave-lengths of the enhanced lines.

For more than thirty years Lockyer's researches and studies were directed to the classification of the stars according to their spectra. Some of the last bulletins he issued from the Hill Observatory, near Sidmouth, were devoted to the same subject. The root idea of his classification as it had been in his studies of the solar spectrum, in the photosphere, spots, reversing-layer, and prominences, was that of the dissociation of the elements at high temperatures. He maintained that the process of stellar evolution is not merely a cooling process, but that there are many stars which are rising in temperature, as well as those which are cooling. The sun and the stars are mainly gaseous bodies, and in such bodies, so long as the density of the gaseous mass remains low, there must be a rise in effective temperature as condensation proceeds. The gaseous mass loses energy by radiation of light and heat at its surface. The process will go on until the condensation has reached such a stage that no longer is radiation at its surface compensated for by the contraction of the body on its center. It will then cool rapidly. This seemingly paradoxical law, that cooling bodies rise in temperature until they cease to be wholly gaseous, was first enunciated by J. Homer Lane, of Washington, in 1892, and has been developed by Ritter. Sir Norman Lockyer starts with

the assumption that a nebula is a swarm of meteorites at a low temperature. This fundamental assumption is negatived by modern spectroscopic studies, such for instance as those made at the Lick Observatory. As condensation proceeds, the temperature of the bodies formed from the nebula, says Lockyer, rises, with a corresponding change in the spectrum, until the highest temperature is reached. We thus have stars with fluted spectra, metallic stars, proto-metallic stars, when dissociation takes place, cleveite-gas stars, and proto-hydrogen stars. Then follow the changes, in reverse order, in the spectra, as the cooling bodies lose temperature by radiation at their surfaces in excess of that gained by condensation. There are therefore two arms to Lockyer's "temperature curve," the one an ascending arm and the other a descending arm. According to this theory, stars of class M are placed on the ascending arm, immediately above the nebulae, and the stars of class N, showing the carbon absorption, immediately following the sun, on the descending arm. The discrimination of stars at higher temperatures into groups of ascending temperature, and groups of cooling stars, is founded upon the appearance of arc and spark lines in the respective spectra in varying intensities. This is the criterion that is employed by W. S. Adams in his spectroscopic determinations of stellar parallaxes. In Lockyer's classification of the stars, those on the ascending branch of the curve differ from those on the descending branch at the same temperature, because the hydrogen lines are thinner and the metallic lines more intense as compared with the same lines in the spectra of stars on the descending branch.

Lockyer labeled his classes of stars by the names of representative stars in the different classes. Thus after the condensing nebula we have the Antarian, Aldebarian, Polarian, Cygnian, Rigelian, Taurian, and Crucian stars. At the summit of the curve stand the Alnitamian and Argonian classes. On the descending arm come in order Achernarian, Algolian, Markabian, Sirian, Procyonian, Arcturian, and Piscian stars. This order would correspond to M, K_5, G, F, A_2, B8, B_3, B_2 ascending; B, O, at the summit; and B_5, B8, A, F_5, G, K, N descending, on the Harvard system of classification.

The central idea of Lockyer's hypothesis has been rejuvenated and modified by Henry Norris Russell, although the data upon which his arrangement rests are derived from the absolute magnitudes, the masses, and the densities of the stars. It agrees, too, with Lockyer's system in making the B class of stars a class apart at the summit of the curve. But the discrimination of the K and M stars into "giants" and "dwarfs" is a profound modification of Lockyer's scheme, in which all the stars of the M class are in an early stage of development. In Russell's classification the "giants" are in an early stage and the "dwarfs" in a late stage. The difference in luminosity is attributed to a difference in volume or size, which means a difference in density, and also to differences in surface brightness.

Lockyer's observations, researches, and theories are summarized in two works, the *Meteoritic Hypothesis* (1890) and *Inorganic Evolution* (1900). These embody an attempt to bring all the known phenomena of the heavens under one category. Nebulae, comets, new stars, variable stars, are all supposed to be due to the clash of meteor streams, from the condensation of which come stars and suns. It was a bold and masterly piece of theorizing. Although there is no chance of its being generally accepted, it contained, as we have seen, many fundamental ideas of modern physics, it evoked much criticism, and acted as an incentive to research.

Our main theme has been the research work of Lockyer in the domain of solar and stellar physics. We can but briefly mention some of his numerous other activities. In 1869 he founded the weekly scientific journal *Nature*, which is the leading journal of the sort probably in the world, and has secured an international circulation. It is in fact indispensable to the scientific worker. For fifty years Sir Norman Lockyer was its editor, ably assisted in later years by the present editor, Sir Richard Gregory. Its form has been practically unmodified from its foundation.

In 1894, as the result of a visit to Egypt, Lockyer became interested in the orientation of temples and their astronomical significance in connection with the heliacal risings and settings of the stars. On returning to England, he extended his researches so

as to embrace the stone circle at Stonehenge. His work, *The Dawn of Astronomy*, contains the results of his measures and of the conclusions he deduces from them.

In 1903–1904, Lockyer was president of the British Association and delivered a stirring address on "The Influence of Brain Power on History." His plea was for the foundation of more national universities, and the address produced a great impression. It eventuated in the foundation of the British Science Guild, for the furtherance of scientific interests, political and social. He became president of the Guild in 1912.

Lockyer was initiated into the game of golf by Professor Tait, who had also suggested to him originally the first ideas of his meteoritic hypothesis. Tait, it is related, once worked out by rigid dynamics the maximum flight of a golf ball when driven from the tee. Next morning his son, Freddy, who was one of the greatest exponents of the game, went out to the links and drove a ball a few yards farther than the range calculated by his father. Lockyer, with his customary enthusiasm in every subject he took up, revised the rules of golf, and published his revision in book form in 1896. This revision had not a little to do with the form of the rules as subsequently adopted at St. Andrews.

Among Lockyer's closest friends was the eminent poet, Sir Alfred Tennyson. Accordingly in a book written in 1910, in conjunction with his daughter, on *Tennyson as a Student and Poet of Nature*, he collected all passages in the poems which dwelt with the scientific aspects of natural phenomena.

In 1913 it was decided to move the Solar Physics Observatory from South Kensington, as the site was required for other buildings in connection with the departments of science and art. Lockyer advocated a hill site, at Salcombe Regis, near Sidmouth, which undoubtedly possesses great advantages in suitability of climate. But the committee to which the matter was referred decided that the observatory should be transferred to Cambridge, and thus be attached to the university. Although Lockyer was an old man, this decision undoubtedly helped to break him up. But with indomitable pluck and admirable courage, he would start the Hill Observatory, as a separate establishment, under its own

corporation. This he succeeded in doing, and he leaves it in a flourishing condition.

Sir Norman Lockyer, created K.C.B. in 1897, died full of academic and scientific honors. He was LL.D. of Aberdeen, Edinburgh, and Glasgow universities, Sc.D. of Cambridge, D.Sc. of Oxford and Sheffield. In 1875 he received the Janssen Medal of the Paris Academy of Sciences, and was elected a corresponding member. From the Royal Society he received the Rumford Medal. He was also an honorary member of the American Academy of Arts and Sciences, and of numerous other foreign academies and societies. He married twice, first Winifred, daughter of Mr. William James, of Trebinshon, near Abergavenny, who died in 1879, and secondly in 1903 Mrs. Bernard E. Broadhurst, daughter of the late Mr. S. E. Browne, of Bridgewater and Clifton. He had four sons and two daughters.

STONYHURST COLLEGE
December 28, 1920

MEASUREMENT OF THE DIAMETER OF α ORIONIS WITH THE INTERFEROMETER[1]

By A. A. MICHELSON and F. G. PEASE

ABSTRACT

Twenty-foot interferometer for measuring minute angles.—Since pencils of rays at least 10 feet apart must be used to measure the diameters of even the largest stars, and because the interferometer results obtained with the 100-inch reflector were so encouraging, the construction of a 20-foot interferometer was undertaken. A very rigid beam made of structural steel was mounted on the end of the Cassegrain cage, and four 6-inch mirrors were mounted on it so as to reduce the separation of the pencils to 45 inches and enable them to be brought to accurate coincidence by the telescope. The methods of making the fine adjustments necessary are described, including the use of two thin wedges of glass to vary continuously the equivalent air-path of one pencil. Sharp fringes were obtained with this instrument in August, 1920.

Diameter of α Orionis.—Although the interferometer was not yet provided with means for continuously altering the distance between the pencils used, some observations were made on this star, which was known to be very large. On December 13, 1920, with very good seeing, no fringes could be found when the separation of the pencils was 121 inches, although tests on other stars showed the instrument to be in perfect adjustment. This separation for minimum visibility gives the angular diameter as 0".047 within 10 per cent, assuming the disk of the star uniformly luminous. Hence, taking the parallax as 0".018, the linear diameter comes out 240×10^6 miles.

Interferometer method of determining the distribution of luminosity on a stellar disk.—The variation of intensity of the interference fringes with the separation of the two pencils depends not only on the angular diameter of the disk but also on the distribution of luminosity. The theory is developed for the case in which $I = I_0 (R^2 - r^2)^n$, and formulae are given for determining n from observations.

Table of values of $\int_0^1 (1-x^2)^{n+\frac{1}{2}} \cos kx\, dx$, for n equal to 0, $\frac{1}{2}$, 1, and 2, and for k up to 600°, is given.

It was shown in *Contributions* Nos. 184 and 185,[2] that the application of interference methods to astronomical measurements is not seriously affected by atmospheric disturbances, and indeed observations by these methods have proved feasible even when the seeing was very poor. The explanation of this apparent paradox lies in the fact that when the whole objective is effective, the atmospheric disturbances, being irregularly distributed over the surface, simply blur the diffraction pattern; but in the case of two isolated pencils too small to be affected by such an integrated disturbance, the resulting interference fringes, though in motion,

[1] *Contributions from the Mount Wilson Observatory*, No. 203.

[2] *Astrophysical Journal*, **51**, 257, 263, 1920.

are quite distinct, unless the period of the disturbances is too rapid for the eye to follow.

When it was found that the interference fringes remain at full visibility with the slits separated by the diameter of the 100-inch mirror, it was decided to build an interferometer with movable outer mirrors (Fig. 1) in order to make tests with separations as great as 20 feet.

The interferometer beam (Plate IV*a* and Fig. 2) was made of structural steel, as stiff and rigid as circumstances of weight and

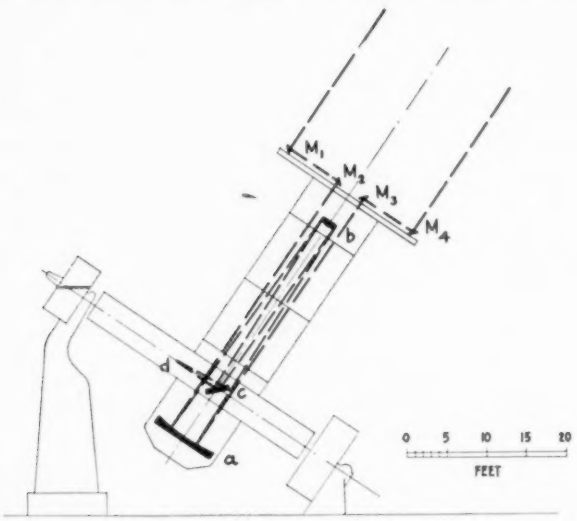


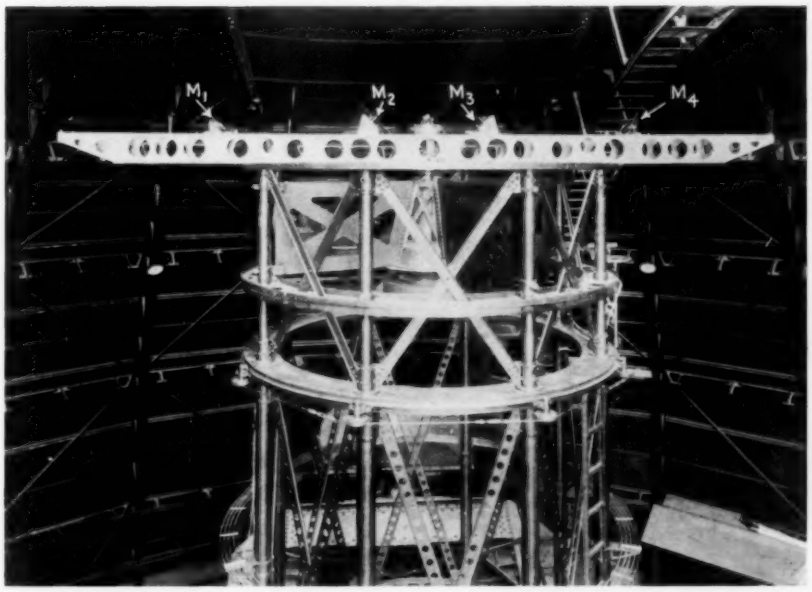
FIG. 1.—Diagram of optical path of interferometer pencils. M_1, M_2, M_3, M_4, mirrors; *a*, 100-inch paraboloid; *b*, convex mirror; *c*, coudé flat; *d*, focus.

operation would permit, for flexure causes a separation of the two pencils, and any vibration as great as one-thousandth of a millimeter blurs the fringes.

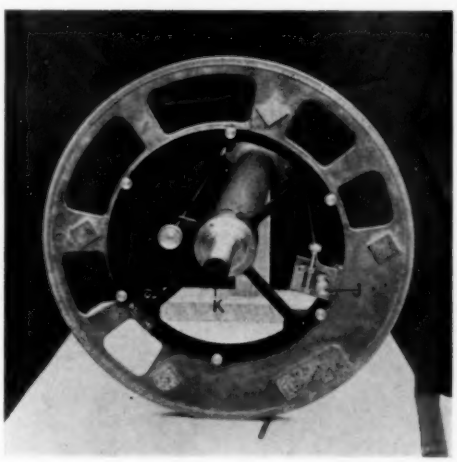
The beam is constructed of two 10-inch channels with flanges turned inward, separated by pieces of 12-inch channel and covered on the bottom with $\frac{3}{16}$-inch (4.75 mm) steel plate (*C*, Fig. 2), all riveted securely together.

To reduce the weight holes were cut wherever the removal of metal would not cause a weakening of the structure. The inner edges of the top flanges were planed true to 0.001 of an inch

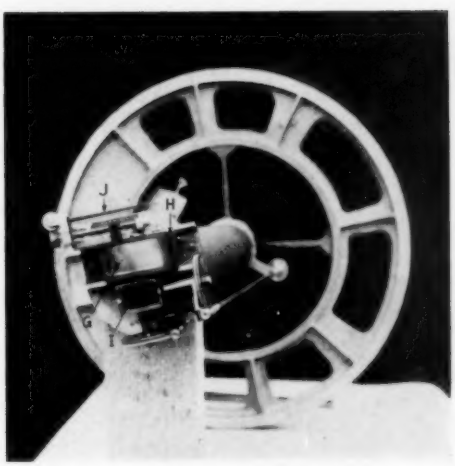
PLATE IV



a



b



c

INTERFEROMETER USED WITH 100-INCH HOOKER REFLECTOR

a. *A*, 20-foot interferometer beam on end of telescope; M_1, M_2, M_3, M_4, mirrors; *D*, Cassegrain cage
b, *c*. Adapter at focus; *J*, rod to shift wedge; *K*, direct-vision prism; *G*, fixed wedge; *H*, movable wedge; *I*, plane-parallel compensator.

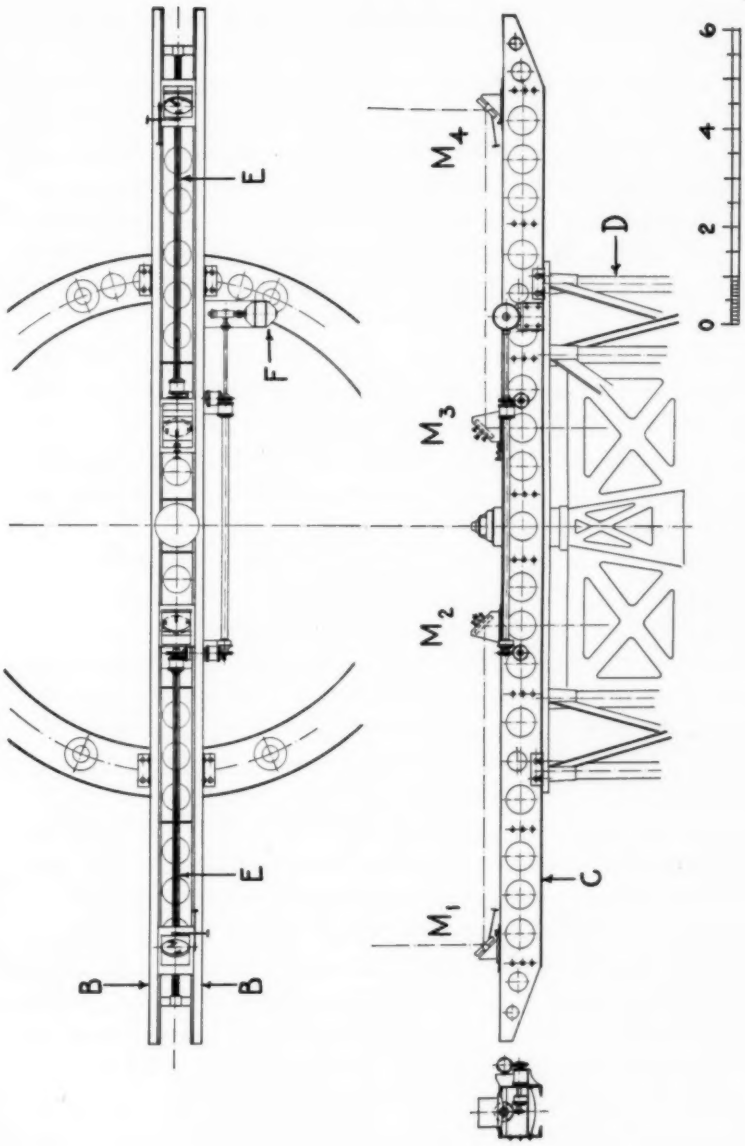


FIG. 2.—Diagram of 20-foot interferometer beam. M_1, M_2, M_3, M_4, mirrors; *B*, *B*, 10-inch channels; *C*, steel plate; *E*, *E*, screws to move outer mirrors; *F*, motor drive for screws; *D*, Cassegrain cage.

(0.025 mm), the beam being supported as it was to be mounted on the telescope.

Four mirrors, M_1, M_2, M_3, M_4 (Figs. 1 and 2 and Plate IV*a*), about 6 inches (152 mm) in diameter, inclined 45° to the base, are mounted on slides; M_2 and M_3 are adjusted by three screws at the back, while M_1 and M_4 are adjustable about two horizontal axes by means of fine screws at the ends of 9-inch (228 mm) lever arms. The mirrors M_2 and M_3 are permanently fixed except that M_3 has a motion of several millimeters along its slide parallel to the beam.

The nearly constant separation of the mirrors M_2 and M_3 by about 45 inches (114.2 cm) gives the fringe pattern a fixed spacing equal to 0.02 mm, easily visible with a magnification of 1600. The mirrors M_1 and M_4 can be shifted along the beam; their distances from M_2 and M_3 must be equal, a condition satisfied as closely as possible by measurement with steel scales.

The beam is mounted on the end of the Cassegrain cage (Plate IV*a* and Fig. 2), which is 11 feet (3.35 m) in diameter, and all observations are made at the Cassegrain focus corresponding to an equivalent focal length of 134 feet (40.84 m). Two pencils from the star are reflected from the outer mirrors M_1 and M_4 to mirrors M_2 and M_3, thence over the ordinary course in the telescope to the paraboloid (*a*, Fig. 1), the convex mirror (*b*, Fig. 1), the coudé flat (*c*, Fig. 1), and finally the focus (*d*, Fig. 1).

M_2 and M_3 are adjusted during the day and M_1 and M_4 on a star at night; and usually after the first setting of a run the image always appears in the field of view of the telescope.

Coincidence of the two interferometer pencils at the focus is obtained by first adjusting the mirrors M_1 and M_4 and then tilting a plane-parallel glass plate, 15 mm thick (*I*, Fig. 3, and Plate IV*c*), in the path of one of the pencils, which also serves to compensate the path of the double wedge mentioned below.

Equality of path in the two interferometer pencils is obtained by first setting the mirrors M_1 and M_4 symmetrically on the beam, as nearly as possible, and then adjusting the double wedge of glass (*G*, *H*, Fig. 3, and Plate IV*c*, 2 feet within the focus) in the path of one of the pencils, the relative motion of the wedges altering the path slowly and continuously.

One of the wedges (*H*, Fig. 3), whose angles are about 10°, can be moved 25 mm either side of its mean position, parallel to the inclined surfaces. One turn of the rod (*J*, Plate IV*b*) shifts this wedge 0.5 mm, thus introducing an equivalent air path of about 0.045 mm. Although fringes can be observed throughout one-third of a turn, corresponding to an air path of 0.015 mm, or about 26 light-waves, the finding of the fringes is notably facilitated by a direct-vision prism (*K*, Plate IV*b*) placed in front of the eyepiece, which permits observation of interference bands with a path-difference of several hundred waves.

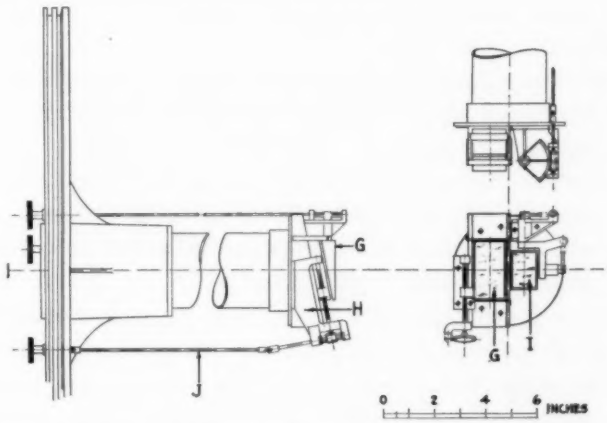


FIG. 3.—Diagram of adapter at focus. *G*, fixed wedge; *H*, movable wedge; *I*, plane-parallel compensator; *J*, rod to shift wedge.

To obtain a series of reference or "zero" fringes the end of the telescope tube is entirely covered, save for two apertures in the beam (in addition to those of mirrors M_2 and M_3), 6 inches (152 mm) in diameter. The pencils entering these apertures pass through the wedges and the compensating plate, respectively, and produce an image of the star in the field of view. When adjusted for coincidence and equality of path, these pencils interfere and produce the zero fringes which cross the reference image.

The interferometer images are next brought into the field of view of the eyepiece and made to coincide a short distance from the zero star, thus forming a second star in the field of view. Usually the adjustment of the mirrors M_1 and M_4 is sufficient to do this and the parallel plate compensator is used only for differential deflection

of the steel beam. As soon as the wedge is moved to equalize the path-difference in the interferometer pencils, the zero fringes disappear and count is made of the turns of the rod required to bring the interferometer fringes into view. The mirror M_3 is then moved a small amount to compensate for this difference, and after several trials both sets of fringes are seen in the field of view crossing their respective images.

Differential refraction between air and glass limits the amount by which the effective thickness of the wedges may differ from that of the compensator, but interferometer fringes have been found with the wedge 20 mm from its mean position, corresponding to a 2-mm difference of air path.

Fringes were obtained with this apparatus in August, 1920, with the mirrors M_1 and M_4 at various distances apart, and, as there was no appreciable deterioration in their visibility at 18 feet (5.49 m) as compared with a separation of 6 feet (1.83 m), it seems reasonable to hope that this distance can be increased to 50 feet (15.24 m) or even to 100 feet (30.48 m). Work was discontinued after this series of experiments and again resumed in December, 1920.

Although provision is only just now being made for continuous alteration of the distance between the mirrors, as is essential in making accurate measurements, it was nevertheless decided to attempt a measurement of the angular diameter of α Orionis, for the calculations of Eddington, Russell, and Shapley, based on estimates of apparent surface brightness, had indicated that this star would be a promising subject for investigation.

The possibility of measuring the angular diameter of a distant object by interference methods depends upon the following considerations.

Let the distribution of light in the disk be represented by

$$I = I_0(R^2 - r^2)^n,$$

r being the distance from the center, R the radius of the star, n the exponent of darkening at the limb. The visibility of the interference bands is

$$V = \frac{1}{P}\sqrt{C^2 + S^2},$$

where

$$C=\int F(x)\cos kx\,dx, \qquad S=\int F(x)\sin kx\,dx,$$

$$P=\int F(x)\,dx, \qquad k=\frac{2\pi b}{\lambda d},$$

in which b is the distance between two pencils entering the interferometer, λ the mean length of the light-waves of the source, and d the distance of the source. $F(x)dx$ is the total intensity of a strip of the source whose width is dx. For a symmetrical source such as a star disk,

$$V=\frac{C}{P}.$$

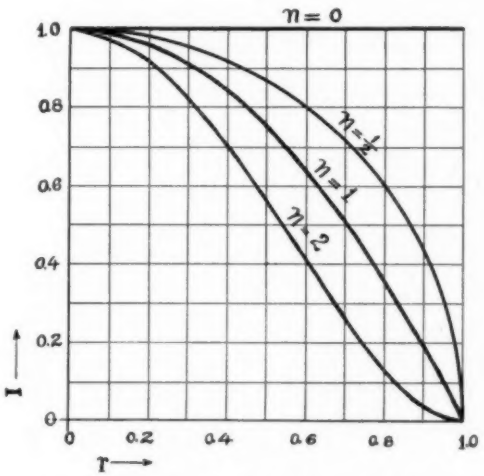


FIG. 4.—Distribution of light in various sources

If the illumination is uniform, $F(x)=\sqrt{R^2-x^2}$, whence

$$V=\frac{\int_0^R \sqrt{R^2-x^2}\cos kx\,dx}{\int_0^R \sqrt{R^2-x^2}\,dx},$$

tables for which have been computed by Airy.

If the illumination can be represented as a function of the distance from the center, $I=(R^2-r^2)^n$, then

$$F(x)=\int_0^{\sqrt{R^2-x^2}}(R^2-x^2-y^2)^n dy$$

which, expanded in series and substituted in V, gives

$$V=\frac{\int_0^R (R^2-x^2)^{\frac{2n+1}{2}}\cos kx\,dx}{\int_0^R (R^2-x^2)^{\frac{2n+1}{2}}\,dx}.$$

This integral has been computed under the direction of Professor Moulton, the results being summarized in the accompanying

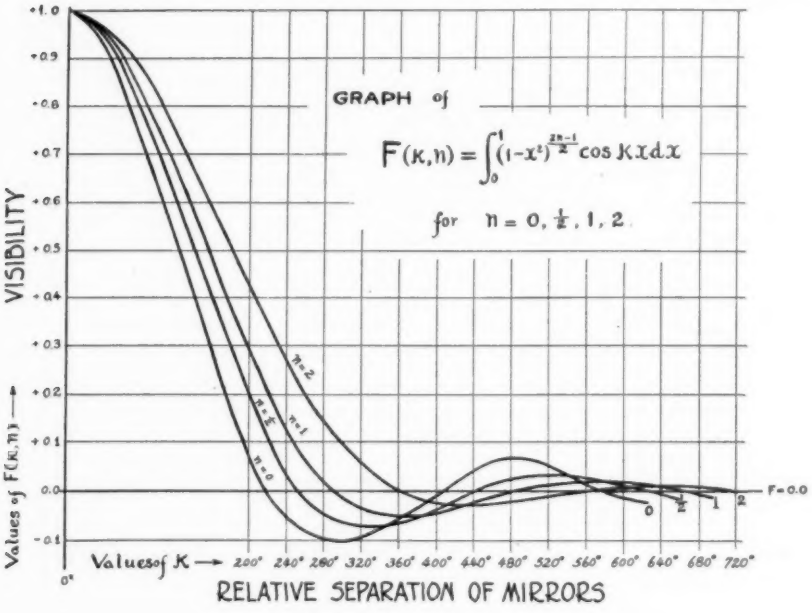


FIG. 5.—Visibility-curves for various sources

table; and in Figure 4 is shown the distribution of light in the source for the values $n=0$, $\frac{1}{2}$, 1, and 2, and in Figure 5 the resulting visibility-curves.

It will be noted that for $n=0$ the first disappearance of the fringes occurs at $k=220°$, while for $n=0.5$, the value is $k=257°$. For this value of n, the corresponding value of the diameter of Betelgeuse would be about 17 per cent greater than given below. (For the sun, the value of n is not far from 0.4.)

VALUES OF

$$F(k, n) = \int_0^1 (1-x^2)^{\frac{2n+1}{2}} \cos kx\, dx$$

$n=0$		$n=0.5$		$n=1$		$n=2$	
k	$F(k,n)$	k	$F(k,n)$	k	$F(k,n)$	k	$F(k,n)$
0°	+0.785	0°	+0.785	0°	+0.785	0°	+0.785
100	+0.507	30	+0.765	40	+0.746	40	+0.761
130	+0.378	60	+0.702	80	+0.663	80	+0.694
160	+0.243	90	+0.607	120	+0.536	120	+0.590
200	+0.065	120	+0.490	160	+0.383	160	+0.468
230	−0.024	150	+0.363	200	+0.237	200	+0.342
240	−0.050	180	+0.238	240	+0.112	240	+0.221
280	−0.100	210	+0.127	280	+0.024	280	+0.123
320	−0.095	240	+0.038	320	−0.029	320	+0.054
360	−0.053	257°27′	0.000	360	−0.045	360	+0.003
400	−0.007	270	−0.024	400	−0.039	400	−0.019
440	+0.036	300	−0.057	440	−0.020	440	−0.024
520	+0.042	330	−0.068	480	−0.001	480	−0.018
600	−0.011	360	−0.059	520	+0.012	520	−0.006
.....	.....	390	−0.040	600	+0.015	560	0.000
.....	.....	420	−0.016	640	+0.005	600	+0.005
.....	.....	450	+0.005	680	−0.004	680	+0.005
.....	.....	480	+0.019	.....	.....	720	+0.002
.....	.....	510	+0.028	.....	.....	.....	.....
.....	.....	540	+0.026	.....	.....	.....	.....
.....	.....	570	+0.019	.....	.....	.....	.....
.....	.....	600	+0.009	.....	.....	.....	.....
.....	.....	630	−0.002	.....	.....	.....	.....

While it may be too much to expect that we shall be able to deduce the actual distribution of the light in the source from observations of the visibility-curve itself, it may be worth while to point out that this is theoretically possible; and perhaps the case will not be entirely hopeless when the requisite skill in making the observations has been obtained by practice.

If b_1 and b_2 are the distances at which the fringes vanish for the first and second times, then the following formula will give a fair approximation to the value of n in the light-curve:

$$n = -1 + 75\left(\frac{b_1}{b_2} - \tfrac{1}{2}\right)^2.$$

Or again, if V_m is the visibility at the first negative maximum (that at $b=0$ being unity),

$$n = 0.22\left(\frac{1}{V_m} - 7.8\right)^{0.7}.$$

It will be seen from this discussion that the measurement sought is that value of the separation of the outer mirrors M_1 and M_4 for which the fringes vanish. This corresponds to the point where the graphs (Fig. 5) cross the horizontal axis, that is, for the value $F(k,n)=0$. A preliminary investigation by Merrill, with the apparatus used by Anderson[1] in the measurement of Capella, revealed in fact a definite decrease in visibility of the fringes of α Orionis for the maximum separation of the slits (100 inches). This was true, moreover, for all position angles, which indicated that the star is not a binary and that the decrease in visibility is to be attributed to a measurable diameter.

On December 13, 1920, after preliminary settings on β Persei with the mirrors separated 81 inches (229 cm) and on β Persei and γ Orionis with a separation of 121 inches, thus insuring that the instrument was in perfect adjustment, it was turned on α Orionis and fringes across the interferometer image were sought for some time, but could not be found. The seeing was very good, and the zero fringes could be picked up at will.

When next turned on α Canis Minoris the fringes stood out on both images with practically no adjustment of the compensating wedge, which furnishes a check on the disappearance of the fringes for α Orionis.

It is clear from these observations that the disappearance of the fringes in the case of α Orionis cannot have been due to any disturbance of the mirrors caused by changes in the position of the telescope, for changes such as those here involved require only a few turns of the rod controlling the compensating wedge to counteract differences in atmospheric path and flexure and bring the fringes again into view. There is therefore no chance that they were simply overlooked in the case of α Orionis.

To observe the recurrence of the fringes near the second maximum for α Orionis, the mirrors were next separated a distance of 13 feet and the telescope turned on α Canis Minoris, fringes appearing across both star images as soon as the component pencils were brought into coincidence. On December 14 and the nights following, the seeing was very poor, the visibility of standard check stars

[1] *Mt. Wilson Contr.*, No. 185; *Astrophysical Journal*, **51**, 263, 1920.

being decidedly less than on the night of December 13; consequently no attempt was made to observe the second maximum and minimum of α Orionis, but attention was turned to other stars, and settings were made on α Ceti, α Tauri, and β Geminorum. The zero fringes were seen in every case, although with slightly decreased visibility; but it was only at rare intervals of better seeing that the interferometer fringes could be seen at all. From this fact it is presumed that there was an actual decrease of visibility for these stars and that some estimate of their diameters can be made with the 20-foot beam. Observations on these and other objects of presumably large diameter are being continued.

Assuming that the effective wave-length for α Orionis is λ 5750, its angular diameter from the formula $\alpha = 1.22\ \lambda/b$ proves to be 0″.047; and with a parallax[1] of 0″.018 its linear diameter turns out to be 240×10^6 miles, or slightly less than that of the orbit of Mars. This value corresponds to a uniformly illuminated disk, while for one darkened at the limb, this result, as mentioned above, would be increased by about 17 per cent. The uncertainty of the measurement of the angular diameter is about 10 per cent.

Cordial acknowledgment is tendered to Director George E. Hale for placing the resources of the Observatory at our disposal and for his enthusiastic co-operation in furthering the investigation.

Mr. J. A. Anderson was present on several occasions and we wish particularly to acknowledge his valuable assistance in checking the measures on December 13.

MOUNT WILSON OBSERVATORY
February 1921

[1] The weighted mean of Adams' spectroscopic parallax, 0″.012, and the trigonometric values of Elkin, 0″.030, and of Schlesinger, 0″.016.

WAVE-LENGTHS OF LINES IN THE IRON ARC FROM GRATING AND INTERFEROMETER MEASURES λ 3370–λ 6750[1]

By CHARLES E. ST. JOHN and HAROLD D. BABCOCK

ABSTRACT

Wave-lengths of iron-arc lines from λ 3370 to λ 6750; grating and interferometer measurements.—To avoid errors due to pole-effect a 12-mm, 5-amp. Pfund arc was used. This arc has also the advantage of yielding very sharp lines. To eliminate instrumental errors, spectrograms made with two Michelson and three Anderson gratings and with four pairs of interferometer plates were compared. Table III contains the mean *results for 1026 lines*, of which 976 were measured on each of from 1 to 62 grating spectrograms and 576 on each of from 1 to 39 etalon spectrograms. The agreement shown indicates that for most of the lines the weighted mean wave-length is accurate to 0.001 A. In the case of 250 stable lines, the agreement with Bureau of Standards measurements is good. But for 46 lines of groups *c*5 and *d*, the Bureau measurements are systematically greater, the mean difference being 0.007 A, due to *pole-effect in the 6-mm, 6-amp. arc.* Of 78 *International Secondary Standards* measured with the interferometer, 62 stable lines came out as follows: 53 within ±0.001, 8 within ±0.002, 2 within ±0.003, and 1 within 0.004 A of the adopted values; while in the case of 16 lines belonging to groups *c*5 and *d*, the International values are systematically greater, the mean difference being 0.007 A, due to pole-effect in the arcs used in the original determinations. Evidently these sources had the same order of pole-effect as the 6-mm, 6-amp. arc. *Ghosts and reversals* gave the same wave-lengths as those obtained from fine lines produced in the core of a lean arc. A comparison of readings from long and short exposures of the same lines showed no *intensity effect* in the case of interferometer measurements.

Spectroscopic measurements.—(1) *Method of reduction of interferometer spectrograms.* The elimination of a gauge plate over the slit and the introduction of a plate constant, $K\lambda$, which may be determined from measurements of the ring diameters alone, greatly reduce the labor of measurement and reduction, without decreasing the precision. (2) *Comparison of grating and interferometer.* The advantages and disadvantages of each are discussed.

I. INTRODUCTION

In a previous paper[2] we discussed the influence of pole-effect in the iron arc upon the measurement of the wave-lengths of certain lines in the lists of adopted secondary and suggested tertiary standards. It was shown that the arc 6 mm in length, carrying a current of 6 amperes, adopted at the Bonn meeting of the Inter-

[1] *Contributions from the Mount Wilson Observatory*, No. 202.

[2] *Mt. Wilson Contr.*, No. 137; *Astrophysical Journal*, **46**, 138, 1917.

national Union for Co-operation in Solar Research, gave a pole-effect of +0.006 A even in its central plane, and that the wave-lengths of the secondary standards belonging to groups *c*5 and *d* were affected to approximately the same amount. This has been confirmed in the present investigation.

In the *Report of the Committee on Standards of Wave-Length* adopted at the Washington meeting of the American Section of the International Astronomical Union[1] the source to be used in the determination of iron standards of wave-length is defined as "the Pfund arc operated between 110 and 250 volts, as convenient, with 5 amperes or less, at a length of 12 millimeters, and used over a central zone at right angles to the axis of the arc not to exceed $1\frac{1}{4}$ millimeters in width." Under these specifications the iron arc yields wave-lengths that appear to be free from pole-effect and is easily workable for wave-lengths shorter than 6000 A. For longer wave-lengths the time of exposure is excessive and pole-effect is not entirely eliminated.

The committee also recommended that independent measurements be made with the grating and with the interferometer, "on the ground that the errors of these two instruments are largely complementary." In the determinations carried out by us, both methods have been employed.

II. APPARATUS AND METHODS

The apparatus used for the interference observations is in the main the same as that described in a previous paper.[2] It is now permanently installed in a double-walled, wooden case with convenient arrangements for projecting the light into it. Various etalons have been used, the plates being either of fused quartz or glass, and the separators of invar or fused quartz. The thickness varied from 2.5 mm to 15 mm; most of the photographs were taken with etalons of 5, 7.5, or 10 mm. The rings were projected upon the slit by a concave mirror having a focal length of 633 mm. No thermostat was used in connection with the interference apparatus, as efficient protection from temperature changes was afforded by

[1] *Proceedings of the National Academy of Sciences*, **6**, 367, 1920.

[2] *Mt. Wilson Contr.*, No. 137; *Astrophysical Journal*, **46**, 138, 1917.

the housing. On the longest exposures no loss of definition can be observed, and the results from these plates show no systematic deviations from those yielded by short exposures. The interferometer plates were several times resilvered by cathodic deposition. On account of the different ratio between its reflection and transmission coefficients, gold was occasionally used for one of the reflecting surfaces. The phase-change corrections have been evaluated in the usual manner by plotting the differences between observed and known wave-lengths for the standards occurring upon each plate. The correction-curves have always been straight lines. No correction for atmospheric dispersion has been applied, since the standards are distributed throughout the extent of each region photographed.

Careful attention has been given throughout the investigation to the adjustment of each part of the apparatus, and no difficulty has been experienced from mechanical disturbances. The etalon was so located with respect to the mirror which projects the rings upon the slit as to bring an image of its diaphragm into focus upon the grating, in accordance with the remark of Buisson and Fabry in their important paper.[1] Furthermore, the size and shape of the diaphragm were so chosen that its image was much smaller than the grating, and the slit-width was so adjusted that diffraction never widened the image beyond the lateral boundaries of the ruled surface. These precautions and the use of large apertures in the projecting systems insured uniform illumination *upon the photographic plate* of several more rings for each line than were actually used for measurement.

As indicated in the paper already referred to, the method of reduction employed at Mount Wilson for interferometer plates is not the same as that described by Buisson and Fabry, Pfund,[2] Burns,[3] and others. These observers derived the fractional order of interference by means of an equation of the form

$$\epsilon = \frac{p\theta^2 D^2}{8L^2},$$

[1] *Journal de physique*, **7**, 169, 1908.

[2] *Astrophysical Journal*, **28**, 197, 1908.

[3] *Bulletin of the Bureau of Standards*, **12**, 179, 1915.

where

ϵ = fractional order of interference for the ring whose linear diameter is D.

θ = angular distance of standard gauge marks in front of the slit, as seen from lens which projects the rings on the slit.

L = linear distance of photographed gauge marks for the same spectral line.

p = order of interference at center of ring system.

This requires, in addition to the photograph of the interference pattern, an exposure to the spectrum with the etalon removed and the gauge plate inserted in front of the slit, from which the value of L is obtained. The quantity θ has also to be determined from independent observations.

A simple transformation of this equation, however, makes possible a marked saving in labor and offers other advantages which are referred to below. If we define by m the magnification of the spectrograph for a given spectral line, and let F be the focal length of the lens or mirror which projects the rings upon the slit, it is readily seen that in the equation above θ^2/L^2 may be replaced by $1/m^2F^2$, giving

$$\epsilon = \frac{pD^2}{8F^2m^2}$$

or more generally, for the n^{th} ring, counting the innermost as the first,

$$n-1+\epsilon = KD_n^2,$$

where K is written for $p/8F^2m^2$. It is evident that both ϵ and K may be determined from this equation if two diameters are measured. For any two consecutive rings, for example the first and second, it is seen that

$$K\lambda = \frac{\lambda}{D_2^2 - D_1^2}.$$

An increase in accuracy may be obtained, however, if the condition is imposed that m be constant for all spectrum lines upon the plate. If e is the thickness of the etalon,

$$K\lambda = \frac{p\lambda}{8F^2m^2} = \frac{2e}{8F^2m^2},$$

which is a constant for the plate considered. The determination of this plate-constant and its application to the problem will be understood from a description of the procedure followed.

Two measurements in reverse directions are made upon the diameters of each of the first two rings for every line upon the plate, except when the fractional order of interference is judged to be less than 0.3, in which case the measures are made upon the second and third rings instead. The two observations upon each diameter are then averaged, and the rough value of the wave-length is divided by the difference of the squares. The number thus derived, in which only four significant figures are retained, is a value of the plate-constant, $K\lambda$, the accuracy of which is then increased as desired by using a sufficient number of lines. The refined value of the plate-constant, divided by the rough wave-length and multiplied by the square of a ring diameter, yields the fractional order directly. The two fractional orders thus obtained from the two rings measured are averaged to produce the final fractional order. In practice it is found that the probable error of a single determination of the plate-constant is about 0.6 per cent, from which it follows that the mean of 35 or 40 values will have a probable error of one part in one thousand, the accuracy aimed at in these measurements. It may be remarked that no systematic difference appeared in the fractional orders yielded by individual rings for the same line.

The assumption of constant magnification in the spectrograph over the field used, while not rigorously true, is found in practice to be permissible in the case of the apparatus employed for this work and also for a plane-grating spectrograph of the Littrow type having a glass lens of 18 feet focal length. An extreme case is found in a quartz spectrograph wherein the normal to the photographic plate stands at an angle of 65° with the optical axis of the camera lens. In the ultra-violet the magnification for this instrument varies as the square root of the wave-length, and the plate-constant is $K\lambda^2$ instead of $K\lambda$. In general the method can be applied without difficulty for any type of spectrograph by a slight modification of the procedure described above.

In the course of the present investigation many determinations of the plate-constants have been made. It has been found that for the same adjustments of the spectrograph, $K\lambda$ for different plates is constant within the errors of observation when the etalon is the same, and that etalons of different thickness give plate-constants in the ratio of the thicknesses, as indicated by the equation above.

Furthermore, it may be pointed out that, when the interference rings are projected by a concave mirror upon the slit of a spectrograph of the type used for this work, it is easy to derive a fundamental instrument-constant from which the plate-constant, $K\lambda$, may be obtained directly from a knowledge of the setting of the spectrograph camera. As indicated above, however, the practice followed in this investigation has been to determine $K\lambda$ from each plate, in which case the instrument-constant serves as a valuable check.

An application of the laws of propagation of errors to the two equations stated above for deriving the fractional order of interference shows that in general the probable error of ϵ is larger for the method of Buisson and Fabry than for the Mount Wilson method. This is to be expected from the fact that in the first method auxiliary quantities θ and L must be observed, the effect of whose probable errors can only be to increase the probable error of the result. A comparison of the results of our interferometer measurements with those of other observers, as well as with values derived from gratings, strengthens the conclusion that the method used by us for deriving fractional orders involves no sacrifice of accuracy as compared to the procedure usually adopted. Furthermore, the simplicity and directness which characterize the new method, the lessening of the necessary photographic and microscopic observations, and the additional numerical checks which become available through its use combine to lend it weight and emphasize its value.

In the region λ 3370–λ 5662 the interferometer plates were measured and reduced for the most part by two observers independently; the weighted means of their results are given in Table I. Over the region of longer wave-lengths most of the measuring was done by one of them, but nearly all of the lines

tabulated were measured and reduced by a third observer upon a selected list of plates. A comparison of the results shows that the various observers are in excellent agreement, no systematic differences of any significance being found between them. It is probable that effects dependent upon personal equation are too small to influence the final values.

The grating measures include only the stable lines from the list published by St. John and Ware,[1] but cover all the lines in the two new series of plates. The old series by St. John and Ware, λ 4118–λ 6500, was taken with the 30-foot Littrow spectrographs on Mount Wilson and in Pasadena, for which Michelson plane gratings with available ruled surfaces 37×114 mm were used in the second-order; scale, 0.88 A per mm. In the new laboratory series the 15-foot concave-grating spectrograph[2] was used in the third order for the region λ 3370–λ 4200. The grating, made by Anderson, has a ruled surface 50×106 mm; scale as used, 1.25 A per mm. From λ 4100 to λ 5658 the 30-foot Littrow spectrograph with an Anderson grating, ruled surface 63×72 mm, was used in the second order; scale, 0.88 A per mm. The new mountain series, λ 3600–λ 5500, was taken with the 30-foot spectrograph of the 60-foot tower telescope. The second order was employed; scale, 0.88 A per mm. The grating, ruled surface 114×160 mm, was made by Anderson and loaned by the Physical Laboratory of the Johns Hopkins University.

The comparators used were constructed in the observatory shop; the screws have been tested and found satisfactory. The standard measuring machines have screws 20 cm long; one specially designed machine with a screw 50 cm long furnished an excellent means for adjusting the reference lines, as its exceptionally long range allows the inclusion of many standards in a single run under constant conditions.

Two methods of reducing the grating data have been used. In one the interpolation between standards was made from a curve whose abscissae are the mean wave-lengths of adjacent secondary

[1] *Mt. Wilson Contr.*, No. 61; *Astrophysical Journal*, **36**, 14, 1912; *Mt. Wilson Contr.*, No. 75; *Astrophysical Journal*, **39**, 5, 1914.

[2] King, *Mt. Wilson Contr.*, No. 84; *Astrophysical Journal*, **40**, 205, 1914.

standards and whose ordinates are the scale-factors for the intervals. In the other, the wave-lengths were calculated from an empirical formula derived from three standards, of the form

$$\lambda = a + bx + cx^2.$$

A curve of corrections was obtained for the deviations of the other standards from the calculated values.

III. THE REGIONS OF THE SPECTRUM COVERED

The interferometer measures extend from λ 3370 to λ 6750. The grating series cover the regions λ 3370–λ 5658 and λ 5975–λ 6500. The gap between λ 5658 and λ 5975, owing to the dearth of suitable standards in this region, is too wide to bridge with the grating. In both the grating and interferometer series all measurable lines were observed. The new laboratory series of grating plates were greatly varied in exposure time in order to obtain a wide range of line-intensity. When feasible, measurements were made upon lines reversed and unreversed and also upon clearly determined ghosts.

IV. SOURCES

For the region λ 3370–λ 6000 the interferometer photographs were taken from a horizontal zone, $1\frac{1}{4}$ mm wide, at right angles to the axis, of a 12-mm Pfund arc carrying 5 amperes or less. For the region λ 6000–λ 6750 the integrated light of a somewhat shorter Pfund arc was used, only stable lines being measured upon the plates.

In the early series by St. John and Ware no particular attention was at first given to the character of the arc, which in general was approximately 5 mm long, or to the portion from which the light was taken. For this reason only the wave-lengths of the lines not subject to pole-effect are retained. In the new grating series the wave-lengths are those given by a 12–14-mm arc with a current of 5 amperes. In the four grating series the wave-lengths of the stable lines are in excellent agreement. The wave-lengths of the lines showing pole-effect depend only upon observations made on the arc recommended by the American committee.

V. RESULTS

The wave-lengths with related data are entered in Table I. The third column gives the group and class. When both group and class are shown the allocation is taken from the paper by Gale and Adams.[1] When no entry appears, the line is practically free from pole-effect, but data are lacking for definite classification. Groups $c5$ and d contain all the lines with recognized positive pole-effect; as our data are insufficient to differentiate the two groups, the lines not in the list of Gale and Adams are provisionally assigned to the major group d. Lines with a negative pole-effect constitute group e.[2] An interrogation point indicates that the evidence for grouping is contradictory. "G" and "I" relate the remarks to grating and interferometer respectively. The dependence of the wave-lengths upon direct measurements, ghosts, or reversals is indicated by "direct," "g," and "r" in the corresponding combination. The other symbols are those suggested by Burns[3] and recommended in the *Report* of the American committee.[4] "A" indicates a probable error less than 0.0007 A; "B," 0.0007 A–0.0012 A, and "C," that the determination is poor; "h" = hazy; "l" = shaded to red; "v" = shaded to violet.

While the interferometer spectrograms were under the microscope, weights 1, 2, and 3 were assigned to the various lines, corresponding to poor, average, or excellent quality. This furnished the basis for combining the observations and also for grouping the final wave-lengths into three classes according to the total weights attached to them. The classes A, B, and C, equivalent to those recommended by the committee, have in general the following limits and numbers of lines:

A = weight from 10 to 159; number of lines 352.
B = weight from 4 to 9; number of lines 111.
C = weight from 1 to 3; number of lines 113.

[1] *Mt. Wilson Contr.*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

[2] St. John and Ware, *Mt. Wilson Contr.*, No. 75, p. 4; *Astrophysical Journal*, **39**, 8, 1914.

[3] *Lick Observatory Bulletin*, **8**, 29, 1913.

[4] *Proceedings of the National Academy of Sciences*, **6**, 367, 1920.

TABLE I

WAVE-LENGTHS OF LINES IN THE IRON ARC (λ 3370–λ 6750), INTERNATIONAL SYSTEM

λ		GROUP	GRATING		INTERFEROMETER		REMARKS
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3370.788	.788	.....	8	A	5	B	
3378.684	.....	.....	7	A	.....	.....	
3379.022	.....	.....	8	B	.....	.....	
3380.115	.....	.....	8	B	.....	.....	
3382.409	.....	.....	6	B	.....	.....	
3383.697	.....	.....	6	A	.....	.....	
3383.982	.987	.....	8	A	1	C	
3392.309	.....	.....	7	A	.....	.....	
3392.656	.656	.....	10	A	2	C	
3394.595	.590	.....	8	B	1	C	G, h
3396.980	.982	.....	8	A	1	C	
3399.336	.337	.....	12	A	8	A	
3401.520	.524	.....	8	A	2	C	
3402.262	.....	.....	8	B	.....	.....	
3404.355	.351	.....	3	C	4	B	G, v
3406.442	.....	.....	6	B	.....	.....	
3406.805	.803	.....	8	A	1	C	
3407.464	.462	.....	16	C	21	A	G, direct, g
3410.171	.....	.....	1	C	.....	.....	
3411.355	.....	.....	6	B	.....	.....	
3413.134	.135	.....	12	A	12	A	
3415.537	.....	.....	7	A	.....	.....	
3417.	.274	*e?*	.....	.....	2	C	
3417.845	.845	.....	12	A	14	A	
3418.508	.510	.....	12	A	6	A	
3422.500	.....	.....	6	B	.....	.....	
3422.658	.665	.....	8	A	3	C	Diff. > error
3424.287	.288	.....	12	A	4	B	
3425.013	.....	.....	8	A	.....	.....	
3426.384	.....	.....	8	B	.....	.....	G, v
3426.638	.....	.....	8	A	.....	.....	
3427.003	.....	.....	6	A	.....	.....	
3427.123	.124	.....	18	B	5	A	G, direct, g
3428.194	.197	.....	8	A	6	A	⊙ Fe, Co
3431.816	.....	.....	1	C	.....	.....	
3440.611	.611	.....	16	C	3	B	
3440.993	.988	.....	12	B	3	C	Diff. > error
3442.673	.....	.....	7	A	.....	.....	
3443.881	.879	.....	12	A	28	A	
3445.152	.152	.....	12	A	13	A	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3445.763	.....	*d*	1	C	.....	.....	
3447.282	.281	.....	8	B	4	B	
3450.333	.331	.....	8	A	5	A	
3451.	.629	.....	.....	.....	1	C	
3451.917	.920	.....	8	A	2	C	
3452.278	.281	.....	8	A	1	C	
3453.023	.....	.....	6	A	.....	.....	
3458.305	.....	.....	6	A	.....	.....	
3459.915	.....	.....	6	A	.....	.....	
3461.	.654	.....	.....	.....	2	C	
3462.	.354	.....	.....	.....	1	C	
3465.866	.863	.....	12	B	27	A	
3475.455	.....	.....	18	A	.....	.....	
3475.652	.....	.....	8	A	.....	.....	
3476.707	.706	.....	11	B	27	A	
3476.854	.....	.....	5	A	.....	.....	
3483.008	.010	.....	6	A	1	C	
3485.340	.345	.....	7	A	7	A	⊙ Fe Co
3489.667	.675	.....	6	A	1	C	
3490.575	.576	.....	17	B	26	A	G, direct, g
3492.	.959	.....	.....	.....	5	B	
3495.286	.289	.....	8	B	5	A	
3497.110	.111	.....	7	B	1	C	G, l
3497.843	.843	.....	11	A	29	A	G, direct, g
3500.563	.....	.....	1	C	.....	.....	
3506.499	.501	.....	3	C	5	A	
3508.	.495	.....	.....	.....	1	C	
3513.819	.820	.....	18	B	30	A	
3515.	.056	.....	.....	.....	3	B	
3521.264	.264	.....	12	A	31	A	
3521.834	.....	.....	6	B	.....	.....	
3524.076	.....	.....	4	B	.....	.....	
3524.240	.....	.....	8	B	.....	.....	
3526.040	.....	.....	12	A	.....	.....	
3526.168	.....	.....	12	A	.....	.....	G, l
3526.378	.....	.....	8	B	.....	.....	
3526.466	.....	.....	8	A	.....	.....	
3526.674	.....	.....	8	B	.....	.....	
3527.793	.798	.....	8	A	3	B	G, v
3529.821	.824	.....	8	A	3	B	⊙ Fe–Co
3530.386	.....	.....	6	A	.....	.....	
3533.009	.....	.....	8	B	.....	.....	
3533.199	.....	.....	10	B	.....	.....	
3536.559	.559	.....	12	A	14	A	
3537.492	.....	.....	1	C	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3537.730	.....	.....	6	A	.....	.....	
3537.897	.....	.....	8	A	.....	.....	
3540.126	.128	.....	7	A	2	C	
3540.710	.....	.....	1	C	.....	.....	
3541.088	.088	.....	12	A	20	A	
3542.080	.080	.....	12	A	16	A	
3543.670	.....	.....	6	A	.....	.....	
3545.644	.641	.....	8	A	4	B	
3547.204	.....	.....	1	C	.....	.....	
3549.869	.....	.....	1	C	.....	.....	
3552.837	.839	.....	8	A	1	C	
3553.744	.747	.....	8	A	1	C	
3554.122	.125	.....	8	A	2	C	
3554.931	.928	.....	16	A	22	A	Diff.>error
3556.889	.883	.....	12	C	11	B	G, l, wgt very low; I, h
3558.522	.518	.....	17	B	33	A	G, direct, g; diff.>error
3559.507	.....	.....	6	A	.....	.....	
3565.383	.381	.....	16	C	23	A	G, h, direct, g
3565.584	.....	.....	8	A	.....	.....	
3568.978	.....	.....	6	A	.....	.....	
3570.103	.100	.....	4	B	1	C	
3571.	.997	.....	6	B	2	C	
3573.893	.....	.....	7	A	.....	.....	G, line on violet
3575.250	.....	.....	5	A	.....	.....	
3575.375	.....	.....	7	B	.....	.....	
3575.983	.....	.....	1	C	.....	.....	
3576.759	.....	.....	5	B	.....	.....	
3581.197	.196	.....	6	A	18	A	G, r; I, r
3581.646	.....	.....	3	C	.....	.....	
3582.202	.201	.....	7	A	1	C	
3583.338	.....	.....	5	B	.....	.....	
3584.664	.665	.....	10	A	2	C	
3584.791	.....	.....	6	A	.....	.....	
3584.961	.....	.....	8	A	.....	.....	
3585.320	.322	.....	5	A	10	A	G, g
3585.709	.710	.....	15	B	1	C	G, direct, g
3586.114	.....	.....	8	A	.....	.....	
3586.987	.987	.....	10	A	29	A	
3587.425	.....	.....	6	A	.....	.....	
3587.753	.....	.....	8	A	.....	.....	
3588.919	.....	.....	6	A	.....	.....	
3589.109	.106	.....	10	B	2	C	
3589.455	.....	.....	8	A	.....	.....	
3594.636	.636	.....	8	A	11	A	
3599.627	.....	.....	6	A	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3602.	.513	.....	.....	.....	1	C	
3603.206....	.207	.....	12	A	11	A	
3603.829....	.....	.....	3	C	.....	.....	G, l
3605.466....	.460	.....	12	C	16	B	Diff.>error; I, h
3606.682....	.682	.....	12	A	28	A	
3608.147....	.....	.....	6	A	.....	.....	
3608.862....	.861	*b*1	13	B	24	A	G, direct, g
3610.164....	.164	.....	12	A	18	A	
3610.704....	.....	.....	1	C	.....	.....	
3612.074....	.073	.....	8	A	4	A	
3612.941....	.....	.....	1	C	.....	.....	
3614.562....	.....	.....	1	C	.....	.....	
3616.573....	.....	.....	8	A	.....	.....	
3617.318....	.....	.....	6	A	.....	.....	
3617.790....	.789	.....	12	A	9	A	
3618.393....	.....	.....	8	A	.....	.....	
3618.773....	.770	*b*1	6	A	22	A	G, g; I, r, direct
3621.465....	.463	.....	18	B	13	A	
3622.009....	.009	.....	15	B	11	A	
3623.190....	.188	.....	11	B	5	A	
3625.	.148	.....	.....	.....	4	A	
3630.353....	.354	.....	6	A	1	C	
3631.104....	.....	.....	11	C	.....	.....	
3631.467....	.466	*b*1	6	B	22	A	G, g; I, r
3632.043....	.043	.....	8	B	2	B	
3632.559....	.....	.....	11	B	.....	.....	
3632.980....	.....	.....	3	C	.....	.....	
3634.336....	.....	.....	11	B	.....	.....	
3636.996....	.....	.....	3	C	.....	.....	
3637.863....	.....	.....	3	C	.....	.....	
3638.300....	.300	.....	23	A	14	A	
3640.392....	.392	.....	23	A	21	A	
3643.628....	.....	.....	11	B	.....	.....	
3645.823....	.....	.....	15	A	.....	.....	
3647.428....	.....	.....	15	B	.....	.....	
3647.846....	.845	*b*1	4	B	22	A	G, r; I, r, direct
3649.305....	.....	.....	19	A	.....	.....	
3649.509....	.511	.....	15	B	11	A	
3650.032....	.....	.....	15	C	.....	.....	
3650.281....	.....	.....	15	A	.....	.....	
3651.471....	.470	.....	26	A	20	A	
3655.468....	.463	.....	18	A	2	C	
3659.520....	.520	.....	21	A	10	A	
3664.541....	.....	*d*	6	A	.....	.....	
3667.265....	.....	*d*	4	C	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3669.152....	.....	.....	1	C	.....	.....	
3669.524....	.524	.....	10	A	9	A	
3670.	.072	.....	.....	.....	1	C	
3674.	.767	.....	.....	.....	1	C	
3676.313....	.315	.....	19	A	10	A	
3677.310....	.....	.....	9	B	.....	.....	
3678.863....	.865	.....	11	A	1	C	
3679.916....	.916	*a*1	10	B	32	A	G, g, r; I, r, direct
3682.226....	.228	.....	16	B	11	A	
3683.059....	.059	.....	12	A	7	A	
3684.113....	.113	.....	24	B	7	A	
3686.002....	.001	*e*	23	B	7	A	
3686.261....	.....	.....	1	C	.....	.....	
3687.101....	.....	.....	15	B	.....	.....	
3687.460....	.460	*b*1	8	B	32	A	G, g, r
3687.657....	.....	.....	14	B	.....	.....	
3689.462....	.463	.....	18	B	11	A	
3690.731....	.731	.....	12	B	4	A	
3693.009....	.009	.....	19	C	14	A	
3695.055....	.056	.....	28	B	12	A	
3697.433....	.433	*d*	16	A	6	A	
3698.613....	.....	.....	5	C	.....	.....	
3699.149....	.....	.....	2	C	.....	.....	
3701.091....	.091	.....	6	A	15	A	
3702.033....	.037	.....	14	A	1	C	
3702.502....	.....	*e*	2	C	.....	.....	
3703.558....	.....	.....	9	B	.....	.....	
3703.699....	.....	*d*	10	C	.....	.....	
3703.826....	.....	.....	9	C	.....	.....	
3704.465....	.466	.....	30	A	9	A	
3705.568....	.568	*a*1	17	C	30	A	G, g, r; I, r, direct
3707.051....	.051	.....	20	A	3	B	
3709.251....	.250	*b*1	26	A	30	A	
3709.537....	.....	.....	4	C	.....	.....	
3711.227....	.227	.....	20	A	2	B	
3711.413....	.....	.....	11	B	.....	.....	
3715.917....	.914	.....	7	B	3	B	
3716.449....	.449	.....	29	A	11	A	
3718.408....	.410	.....	20	A	1	C	
3719.939....	.937	*a*1	23	A	23	A	G, r; I, r, direct
3722.030....	.....	.....	2	B	.....	.....	
3722.564....	.565	*a*1	18	A	31	A	G, direct, g, r; I, r, direct
3724.380....	.380	.....	8	A	18	A	
3725.500....	.....	.....	1	C	.....	.....	
3726.929....	.....	*e*	18	A	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3727.098	.....	.....	22	A	.....	.....	
3727.622	.623	*b*1	10	A	30	A	G, g
3727.811	.....	.....	19	A	.....	.....	
3728.670	.....	.....	3	C	.....	.....	
3730.388	.391	.....	19	A	1	C	
3730.947	.948	.....	15	A	1	C	
3731.377	.375	.....	13	A	1	C	
3732.400	.398	.....	34	A	18	A	
3733.319	.321	*a*1	25	A	28	A	G, direct, g, r; I, r, direct
3734.870	.866	*b*1	13	A	19	A	Diff.>error; I, r, direct
3735.327	.....	.....	22	A	.....	.....	
3737.135	.134	*a*1	25	A	25	A	G, g, r; I, r, direct
3738.309	.309	.....	20	A	9	A	
3739.122	.....	.....	2	B	.....	.....	
3739.529	.....	*d*	15	A	.....	.....	
3740.248	.250	*d*	10	B	1	C	
3742.624	.622	.....	5	B	1	C	
3743.365	.366	*b*1	41	A	32	A	G, direct, g
3743.470	.....	.....	3	B	.....	.....	
3744.108	.106	*e*	15	A	1	C	
3745.564	.562	*a*1	38	A	14	A	G, direct, g
3745.902	.904	*a*1	53	A	14	A	G, direct, g, r
3746.488	.....	.....	2	B	.....	.....	
3746.933	.....	*e*?	18	A	.....	.....	
3748.264	.264	*a*1	49	A	22	A	G, direct, g, r; I, r, direct
3748.971	.....	*e*	19	A	.....	.....	
3749.490	.489	*b*1	44	A	23	A	G, direct, g, r; I, r, direct
3751.061	.....	.....	3	C	.....	.....	
3751.822	.....	.....	2	C	.....	.....	
3752.422	.....	.....	2	B	.....	.....	
3753.156	.....	.....	2	C	.....	.....	
3753.615	.614	.....	25	A	15	A	
3754.508	.....	*e*	3	B	.....	.....	
3756.071	.....	.....	3	B	.....	.....	
3756.942	.941	.....	17	A	2	B	
3757.461	.....	.....	6	B	.....	.....	
3758.238	.236	*b*1	48	A	22	A	G, direct, g, r; I, r, direct
3760.053	.054	.....	24	A	12	A	
3760.534	.536	.....	12	B	3	C	G, .524, h, v
3761.418	.....	.....	2	C	.....	.....	
3763.791	.791	*b*1	51	A	26	A	I, r, direct
3765.543	.543	*b*1	16	B	13	A	G, g near
3767.195	.195	*b*1	50	A	28	A	G, direct, g, r; I, r, direct
3768.	.032	.....	.....	.....	1	C	
3773.701	.....	*e*	1	C	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3774.827	.827	.....	30	A	6	A	
3775.862	.....	.....	2	C	.....	.....	
3776.458	.458	.....	20	A	6	A	
3777.063	.....	.....	1	C	.....	.....	
3777.450	.....	.....	6	B	.....	.....	
3778.511	.....	.....	8	A	.....	.....	
3778.699	.....	.....	4	B	.....	.....	
3779.488	.488	.....	2	C	1	B	G, l
3781.189	.190	.....	4	B	1	B	
3781.940	.....	.....	2	C	.....	.....	
3782.124	.....	.....	2	C	.....	.....	
3782.452	.....	.....	2	C	.....	.....	
3782.610	.....	.....	1	C	.....	.....	
3785.708	.....	.....	2	C	.....	.....	
3785.950	.949	.....	34	A	5	A	
3786.178	.....	.....	11	C	.....	.....	
3786.679	.680	.....	32	A	4	A	
3787.166	.....	.....	2	C	.....	.....	
3787.885	.885	*b*1	33	A	31	A	G, direct, r
3789.180	.....	.....	15	A	.....	.....	
3789.430	.....	*d*	2	C	.....	.....	
3789.572	.....	.....	5	C	.....	.....	
3790.005	.097	.....	33	A	16	A	
3790.658	.....	.....	3	C	.....	.....	
3790.758	.....	.....	10	B	.....	.....	
3791.506	.....	.....	3	C	.....	.....	
3792.158	.....	.....	7	B	.....	.....	
3793.480	.....	.....	9	B	.....	.....	
3793.874	.....	.....	11	C	.....	.....	
3794.342	.342	.....	32	A	4	B	
3795.006	.005	*b*1	57	A	27	A	G, direct, r
3795.533	.....	.....	4	C	.....	.....	
3797.518	.519	.....	37	A	7	A	
3797.950	.....	.....	2	C	.....	.....	
3798.515	.514	.....	62	A	29	A	G, direct, g, r
3799.551	.551	.....	60	A	31	A	G, direct, r
3801.683	.682	.....	17	A	2	C	
3801.806	.....	.....	4	C	.....	.....	
3801.977	.....	*e*	4	C	.....	.....	
3802.285	.....	.....	5	C	.....	.....	
3804.015	.....	.....	5	C	.....	.....	
3805.346	.346	.....	36	A	18	A	
3806.205	.....	*d*	19	C	.....	.....	
3806.700	.700	.....	25	A	11	A	
3807.540	.541	.....	32	A	13	A	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3808.288	.....	.....	4	C	.....	.....	
3808.733	.733	.....	25	A	2	B	
3810.761	.....	.....	25	B	.....	.....	
3811.894	.....	.....	10	C	.....	.....	
3812.967	.968	.....	37	A	32	A	G, direct, r
3813.061	.....	.....	10	C	.....	.....	
3813.640	.....	.....	17	C	.....	.....	
3814.527	.529	.....	24	A	1	C	
3815.843	.843	*b*1	24	A	23	A	G, r; I, r, direct
3816.342	.....	.....	24	A	.....	.....	
3820.430	.429	.....	53	A	21	A	G, direct, g, r; I, r, direct
3821.181	.183	.....	41	A	11	A	
3821.836	.....	.....	22	B	.....	.....	
3824.076	.....	.....	8	B	.....	.....	
3824.444	.446	.....	25	A	26	A	G, r
3825.406	.....	.....	3	C	.....	.....	
3825.884	.885	*b*1	40	A	24	A	G, g, r; I, r, direct
3826.838	.....	.....	3	C	.....	.....	
3827.574	.....	.....	10	B	.....	.....	
3827.826	.826	*b*1	28	A	27	A	G, g, r
3829.127	.....	*d*	3	B	.....	.....	
3830.759	.....	.....	3	B	.....	.....	
3830.852	.....	*d*	2	C	.....	.....	
3833.312	.314	.....	39	A	7	A	
3834.224	.225	*b*1	32	A	25	A	G, g, r; I, r, direct
3836.334	.334	.....	25	A	7	A	
3837.134	.....	.....	4	C	.....	.....	
3839.260	.259	.....	23	A	9	A	
3840.439	.439	.....	28	A	23	A	G, g, r
3841.051	.052	.....	50	A	23	A	G, direct, g, r
3843.260	.260	.....	26	A	16	A	
3845.694	.....	.....	4	C	.....	.....	
4846.414	.....	.....	12	B	.....	.....	
3846.805	.804	.....	30	A	12	A	
3849.970	.971	.....	32	A	28	A	G, direct, r
3850.821	.821	.....	20	A	21	A	
3852.576	.576	.....	32	A	9	A	
3855.848	.....	*d*	3	C	.....	.....	
3856.372	.374	.....	28	A	29	A	G, g, r; I, r, direct
3859.216	.215	.....	30	A	7	A	G, direct, g, r
3859.915	.914	.....	29	A	22	A	I, r, direct
3861.343	.....	.....	15	B	.....	.....	
3865.529	.527	.....	31	A	32	A	G, direct, r
3867.221	.222	.....	23	A	8	A	
3871.752	.751	.....	14	B	2	C	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3872.506....	.505	.....	34	A	29	A	G, direct, g, r
3873.764....	.765	.....	21	A	8	A	
3876.045....	.....	.....	15	A	.....	.....	
3878.023....	.022	.....	26	A	22	A	G, direct, r
3878.576....	.575	.....	24	B	20	A	G, direct, g, r; I, r, direct
3883.284....	.284	.....	11	B	1	C	
3884.363....	.358	*b*	17	B	3	C	
3885.512....	.514	*b*	24	C	4	B	
3886.286....	.285	*a*1	17	C	20	A	G, direct, r; I, r, direct
3887.052....	.055	*b*1	27	B	20	B	G, direct, g, r
3888.518....	.518	*b*1	23	B	29	A	G, direct, g, r
3890.846....	.....	*b*	16	B	.....	.....	
3891.934....	.926	*b*	16	C	3	B	Diff.>error
3893.396....	.396	.....	10	B	5	A	G, direct, g
3893.926....	.....	.....	6	B	.....	.....	
3894.007....	.....	.....	1	C	.....	.....	
3895.660....	.660	*a*1	17	B	30	A	
3897.451....	.....	.....	5	B	.....	.....	
3897.898....	.....	*b*	10	B	.....	.....	
3899.039....	.....	*e*	2	C	.....	.....	
3899.713....	.710	*a*1	14	B	28	A	G, direct, g
3900.521....	.....	.....	6	B	.....	.....	
3902.948....	.950	*b*1	4	A	21	A	G, g
3903.904....	.....	*b*	16	A	.....	.....	
3906.486....	.484	*a*1	13	C	23	A	
3906.750....	.....	.....	12	A	.....	.....	
3907.466....	.....	.....	3	C	.....	.....	
3907.940....	.936	*b*	16	C	6	B	
3909.666....	.....	.....	7	B	.....	.....	
3909.	.832	*b*	.....	.....	2	B	
3910.848....	.847	.....	8	B	2	C	
3913.637....	.637	*b*	13	A	5	A	
3916.737....	.....	*b*	14	B	.....	.....	
3917.186....	.186	*a*	16	A	6	A	
3918.321....	.....	.....	14	B	.....	.....	
3918.420....	.....	.....	13	B	.....	.....	
3918.646....	.....	*b*	14	B	.....	.....	
3919.071....	.....	*b*	13	A	.....	.....	
3920.262....	.260	*a*1	11	B	19	A	
3920.841....	.....	*d*	3	C	.....	.....	
3922.915....	.916	*a*1	11	C	17	A	
3925.648....	.....	*b*	10	B	.....	.....	
3925.945....	.950	*a*1	15	B	5	C	
3927.923....	.924	*a*	18	B	16	A	
3928.087....	.....	*d*	10	B	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3929.116	.....	.....	3	C	.....	.....	
3929.210	.....	.....	3	C	.....	.....	
3930.301	.300	*a*1	18	C	16	A	G, direct, r
3931.124	.....	.....	6	C	.....	.....	
3932.630	.631	*b*	12	A	3	B	
3932.919	.....	.....	2	B	.....	.....	
3933.608	.....	.....	3	C	.....	.....	
3935.817	.817	*b*	15	B	7	A	
3937.330	.332	*b*	5	B	2	C	
3940.883	.883	*a*	19	B	7	A	
3941.285	.....	*d*	6	C	.....	.....	
3942.445	.444	*b*	10	B	8	A	
3943.341	.....	*b*	4	B	.....	.....	
3944.750	.....	.....	2	C	.....	.....	
3944.892	.....	*b*	6	B	.....	.....	
3945.121	.....	*b*	7	B	.....	.....	
3947.004	.....	.....	7	B	.....	.....	
3947.535	.....	*b*	12	B	.....	.....	
3948.107	.....	*d*	14	B	.....	.....	
3948.780	.781	*b*	15	A	4	B	
3949.958	.958	*b*	15	A	4	A	
3951.168	.172	*b*	15	C	3	C	
3952.607	.607	*b*	15	A	6	A	
3953.158	.....	*b*	9	B	.....	.....	
3955.354	.....	*d*	4	C	.....	.....	
3955.958	.....	*b*	2	C	.....	.....	
3956.463	.459	*b*	9	B	4	B	
3956.681	.682	*b*4	12	A	6	A	
3957.029	.....	*d*	12	A	.....	.....	
3960.286	.....	.....	4	C	.....	.....	
3961.149	.....	.....	4	C	.....	.....	
3963.110	.....	*d*	8	C	.....	.....	
3964.520	.528	*b*	8	C	1	C	
3965.513	.....	*d*	2	C	.....	.....	
3966.067	.067	*b*	14	A	7	A	
3966.632	.....	*e*	13	B	.....	.....	
3966.826	.....	*e*	2	C	.....	.....	
3967.424	.424	.....	4	B	2	B	
3967.966	.....	.....	6	A	.....	.....	
3969.261	.262	*b*1	27	B	11	A	G, direct, r
3969.630	.....	.....	5	B	.....	.....	
3970.264	.....	.....	2	C	.....	.....	
3970.393	.....	*b*	3	C	.....	.....	
3971.327	.327	*b*	20	A	9	A	
3973.657	.....	*b*	5	B	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
3974.399	.....	.....	2	C	.....	.....	
3976.617	.617	*d*	7	B	1	C	
3976.867	.....	.....	6	C	.....	.....	
3977.745	.745	*b*4	14	A	10	A	
3981.776	.777	*b*	16	B	5	B	
3983.963	.961	*b*	15	A	10	A	
3985.395	.....	.....	5	C	.....	.....	
3986.178	.178	*b*	11	B	1	C	
3989.861	.....	.....	5	C	.....	.....	
3990.381	.....	*b*	7	B	.....	.....	
3994.119	.....	*b*	7	C	.....	.....	
3995.201	.....	*d*	2	C	.....	.....	
3995.998	.....	*b*	5	B	.....	.....	
3996.970	.....	*b*	7	C	.....	.....	
3997.396	.396	*b*4	14	A	11	A	
3998.058	.059	*b*	13	A	9	A	
4000.268	.....	.....	2	C	.....	.....	
4000.468	.....	*b*	2	C	.....	.....	
4001.669	.666	*b*	8	C	4	B	
4003.766	.....	*b*	4	B	.....	.....	
4004.834	.....	*b*	2	C	.....	.....	
4004.978	.....	*b*	2	C	.....	.....	
4005.247	.247	*b*1	16	B	13	A	G, direct, r
4006.316	.....	*b*	7	C	.....	.....	
4006.633	.....	*b*	5	C	.....	.....	
4007.279	.....	*b*	14	B	.....	.....	
4009.717	.717	*a*	14	B	11	A	
4013.643	.....	.....	1	C	.....	.....	
4013.824	.....	*b*	5	C	.....	.....	
4014.536	.536	*b*	14	A	9	A	
4017.157	.158	*b*	13	B	4	B	
4018.284	.....	.....	2	C	.....	.....	
4021.871	.872	*b*	8	A	12	A	
4024.111	.....	.....	2	C	.....	.....	
4024.738	.735	*d*	3	C	2	C	
4030.501	.....	*d*	7	B	.....	.....	
4040.652	.....	*e*	2	C	.....	.....	
4044.618	.615	*b*	2	C	3	C	
4045.816	.817	*b*1	7	B	5	A	G, .807 g
4051.925	.....	.....	2	C	.....	.....	
4052.314	.....	.....	2	C	.....	.....	
4062.448	.447	*b*	9	B	11	A	
4063.288	.....	*d*	7	B	.....	.....	
4063.596	.599	*b*1	6	C	7	A	G, .587 g
4066.983	.983	*b*	7	B	5	B	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
4067.276	.275	*b*	6	C	3	C	
4067.987	.985	*b*	7	B	3	B	
4070.	.768	.....	.....	.....	2	C	
4071.740	.743	*b*1	6	C	10	A	G, .733 g
4074.796	.....	.....	3	C	.....	.....	
4076.234	.....	.....	2	C	.....	.....	
4076.638	.638	*b*	4	B	7	A	G, 3057 4th order coincides
4076.812	.....	.....	2	C	.....	.....	
4078.367	.....	.....	2	C	.....	.....	
4079.850	.....	*b*	3	C	.....	.....	
4080.228	.....	*b*	1	C	.....	.....	
4082.127	.....	.....	2	C	.....	.....	
4083.782	.....	.....	2	C	.....	.....	
4084.501	.500	*d*	7	B	1	C	
4085.013	.....	*b*	4	B	.....	.....	
4085.314	.....	*b*	7	B	.....	.....	
4089.227	.....	.....	2	C	.....	.....	
4091.563	.....	.....	2	C	.....	.....	
4092.289	.....	.....	2	C	.....	.....	
4095.980	.975	*b*	7	C	10	A	
4097.101	.....	.....	2	C	.....	.....	
4098.186	.184	*b*	6	C	7	A	
4100.750	.744	.....	2	C	6	A	
4101.274	.....	*d*	2	C	.....	.....	
4107.495	.494	*b*	9	A	16	A	
4109.072	.....	.....	2	C	.....	.....	
4109.812	.808	*b*	8	B	13	A	Diff. > error
4112.974	.....	*d*	2	C	.....	.....	
4114.454	.450	*b*	6	C	11	A	
4114.959	.....	.....	2	C	.....	.....	
4118.552	.550	*b*	18	B	19	A	
4120.215	.211	*b*	3	C	7	A	
4121.810	.808	.....	14	B	7	A	
4122.524	.525	*b*	3	B	7	B	
4123.750	.....	.....	3	B	.....	.....	
4125.624	.....	*d*	1	C	.....	.....	
4125.886	.....	.....	2	A	.....	.....	
4126.193	.194	*b*	3	B	1	C	
4127.615	.614	.....	20	B	12	A	
4127.809	.....	.....	3	B	.....	.....	
4132.061	.063	*b*1	21	B	17	A	
4132.905	.906	*b*	6	B	9	A	
4133.871	.....	*d*	1	C	.....	.....	
4134.684	.684	*b*4	19	A	18	A	
4136.514	.....	*d*	6	B	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
4137.006....	.003	*b*	7	B	14	A	⊙ enh Mn
4139.935....	.....	*a*	1	C	.....	.....	
4143.421....	.420	*b*	17	A	10	A	
4143.872....	.874	*b*1	11	B	14	A	
4147.676....	.675	*b*	26	A	14	A	
4149.374....	.374	*e*	8	A	5	B	
4150.260....	.....	*d*	6	C	.....	.....	
4152.173....	.174	.....	8	B	3	C	
4153.907....	.909	*d*	16	A	4	B	
4154.111....	.....	.....	2	C	.....	.....	
4154.505....	.504	*b*	36	A	5	B	
4154.813....	.815	*d*	16	A	1	C	
4156.805....	.804	*b*	32	A	15	A	
4157.792....	.788	*d*	15	B	2	C	
4158.801....	.800	*d*	8	B	4	B	
4170.907....	.906	*b*	31	A	1	C	
4171.698....	.....	*d*	1	C	.....	.....	
4172.128....	.....	.....	7	A	.....	.....	
4172.751....	.....	*a*	7	B	.....	.....	
4173.324....	.....	*b*	6	B	.....	.....	
4173.928....	.....	*a*	6	B	.....	.....	
4174.919....	.....	*a*	18	A	.....	.....	
4175.642....	.642	*b*	43	A	13	A	
4176.574....	.572	*e*	10	B	7	B	⊙ Fe–Mn
4177.599....	.599	*a*	17	B	8	A	
4181.760....	.760	*b*	24	A	21	A	
4182.386....	.....	*b*	4	A	.....	.....	
4184.897....	.896	*b*	35	A	17	A	
4187.047....	.045	*d*	12	A	11	A	
4187.804....	.805	*d*	12	A	11	A	
4191.439....	.438	*d*	12	A	11	A	
4191.687....	.....	*e*?	4	C	.....	.....	
4195.340....	.338	*d*	10	A	4	B	
4195.617....	.....	.....	1	C	.....	.....	
4196.220....	.....	*d*	6	C	.....	.....	
4198.312....	.312	*d*	3	C	11	A	
4198.647....	.....	*d*	5	C	.....	.....	
4199.099....	.101	*b*	31	A	18	A	
4200.932....	.....	*e*	4	C	.....	.....	
4202.033....	.034	*b*1	37	A	18	A	
4203.988....	.990	*b*3	24	A	12	A	
4205.548....	.....	.....	2	C	.....	.....	
4206.704....	.703	*a*	6	B	5	A	
4207.133....	.132	*b*	7	C	5	B	
4208.612....	.....	*b*	7	B	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
4210.355....	.352	*c*5	13	A	9	A	Diff. > error
4213.652....	.652	*b*	8	B	8	A	
4215.432....	.....	*b*	4	C	.....	.....	
4216.188....	.188	*b*3	20	A	20	A	
4217.554....	.552	*d*	9	B	4	B	
4219.367....	.367	*b*	36	A	18	A	
4220.348....	.350	*b*	7	B	1	C	
4222.222....	.221	*d*	9	B	10	A	
4224.179....	.177	*e*	22	B	7	B	
4225.463....	.462	*d*	10	B	1	C	
4225.958....	.....	*b*	7	B	.....	.....	
4226.428....	.....	*b*	7	B	.....	.....	
4227.437....	.436	*d*5	10	A	11	A	
4229.518....	.....	.....	1	C	.....	.....	
4229.762....	.....	.....	1	C	.....	.....	
4233.142....	.....	*d*?	2	C	.....	.....	⊙ Mn–Fe
4233.611....	.610	*d*5	10	B	11	A	
4235.	.945	*d*5	.....	.....	12	A	
4237.164....	.....	.....	2	C	.....	.....	
4238.029....	.....	*d*?	6	B	.....	.....	
4238.818....	.819	*d*	10	B	4	B	
4239.849....	.849	*a*	1	C	1	C	
4240.374....	.....	.....	3	C	.....	.....	
4242.732....	.....	.....	2	C	.....	.....	
4245.264....	.261	*b*	10	C	2	B	
4246.092....	.....	*b*	4	C	.....	.....	
4247.436....	.434	*d*	10	A	7	A	
4248.230....	.....	*b*	7	B	.....	.....	
4250.128....	.126	*c*5	12	C	7	A	
4250.792....	.792	*b*	42	A	16	A	
4254.337....	.340	*d*	5	A	3	B	Cr
4258.322....	.....	*a*	5	B	.....	.....	
4258.621....	.....	.....	1	C	.....	.....	
4258.958....	.....	*e*	1	C	.....	.....	
4260.482....	.482	*c*2	8	B	15	A	
4264.211....	.....	*d*	1	C	.....	.....	
4265.262....	.....	.....	1	C	.....	.....	
4266.970....	.971	*b*	7	B	3	B	
4267.831....	.832	*b*	6	A	3	B	
4268.	.746	*b*	.....	.....	1	C	
4271.163....	.159	*d*	7	C	5	C	
4271.766....	.766	*b*1	33	B	11	A	
4274.	.802	.....	.....	.....	2	B	Cr
4276.686....	.....	?	1	C	.....	.....	
4278.236....	.....	?	1	C	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
4279.866	.....	?	1	C	.....	.....	
4282.408	.408	b_1	30	A	20	A	
4285.448	.449	b	6	B	4	B	
4288.150	.....	.....	5	C	.....	.....	
4290.384	.....	.....	3	C	.....	.....	
4290.872	.....	.....	2	C	.....	.....	
4291.465	.....	a_3	7	B	.....	.....	
4294.130	.130	b_2	8	C	19	A	
4298.044	.042	.....	6	A	4	B	
4299.243	.242	d_5	8	B	11	A	
4302.	.193	.....	.....	.....	1	C	
4304.554	.....	.....	2	C	.....	.....	
4305.454	.459	b	2	C	3	C	Fe, Cr?
4307.908	.908	b_1	48	A	7	A	
4309.038	.....	?	1	C	.....	.....	
4315.090	.090	b_3	45	A	19	A	
4321.803	.....	.....	3	C	.....	.....	
4325.766	.767	b_1	52	A	8	A	
4327.103	.101	b	6	B	1	C	
4337.052	.052	b_3	47	A	19	A	
4338.262	.....	.....	1	C	.....	.....	
4343.259	.....	d	4	B	.....	.....	
4343.701	.....	.....	5	B	.....	.....	
4346.560	.560	.....	5	B	1	B	
4348.941	.....	?	1	C	.....	.....	
4351.551	.551	b	6	C	6	A	
4352.739	.740	b_3	20	A	20	A	
4358.508	.506	b	6	B	4	B	
4367.582	.584	b	17	A	5	B	
4367.908	.....	a	6	B	.....	.....	
4369.776	.777	b_3	30	A	20	A	
4373.563	.567	.....	5	B	1	C	
4375.934	.934	a_3	40	A	26	A	
4383.550	.550	b_1	.....	A	8	A	
4387.898	.900	b	6	B	2	C	
4388.414	.415	d?	10	B	2	C	
4389.247	.246	a	7	B	1	C	
4390.955	.957	b	6	B	5	A	
4401.295	.....	d	6	A	.....	.....	
4404.755	.755	b_1	45	A	12	A	
4407.715	.716	c_4	24	A	7	A	
4408.420	.420	c_4	30	A	18	A	
4409.125	.....	?	1	C	.....	.....	
4415.128	.128	b_1	53	A	18	A	
4422.573	.573	b_3	40	A	32	A	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
4427.314....	.314	*a*3	30	A	38	A	
4430.621....	.620	*c*4	35	A	34	A	
4432.574....	.....	.....	7	B	.....	.....	
4433.225....	.....	*e*	12	A	.....	.....	
4433.795....	.....	*d*	6	C	.....	.....	
4435.153....	.....	*a*	11	A	.....	.....	
4439.885....	.....	.....	7	B	.....	.....	
4442.345....	.345	*c*4	11	A	34	A	
4442.837....	.....	.....	9	B	.....	.....	
4443.197....	.200	*b*3	31	A	32	A	Diff.>error
4446.844....	.....	*d*	9	B	.....	.....	
4447.136....	.....	.....	4	A	.....	.....	
4447.723....	.724	*c*4	32	A	37	A	
4450.323....	.....	.....	6	C	.....	.....	
4454.386....	.386	*b*3	12	B	28	A	
4454.658....	.....	*d*	2	C	.....	.....	
4455.035....	.....	?	2	C	.....	.....	Probably Mn
4456.334....	.....	.....	3	C	.....	.....	
4459.123....	.125	*c*4	27	A	39	A	
4461.656....	.656	*a*3	22	A	34	A	
4461.992....	.....	*d*	1	C	.....	.....	
4466.556....	.557	*b*4	22	A	37	A	
4469.386....	.384	*d*	5	B	18	A	
4472.724....	.....	?	3	C	.....	.....	
4476.026....	.023	*b*4	16	C	29	A	Double in vacuum. Cf. *Astrophysical Journal*, **44**, 331, 1916.
4479.615....	.....	.....	4	A	.....	.....	
4480.145....	.....	.....	5	B	.....	.....	
4481.624....	.....	.....	3	C	.....	.....	
4482.	.174	*a*	.....	.....	14	A	G, too close; I, meas. at orders 22250, 32890
4482.	.260	*a*	.....	.....	14	A	
4484.231....	.229	*d*	4	B	13	A	
4485.681....	.682	*e*?	5	A	4	B	I, h
4488.143....	.....	.....	3	B	.....	.....	
4488.920....	.....	.....	2	C	.....	.....	
4489.745....	.744	*a*3	13	A	23	A	
4490.087....	.087	.....	3	B	2	C	⊙ Mn–Fe; I, fringes poor
4490.776....	.....	.....	5	B	.....	.....	
4494.572....	.570	*c*4	40	A	38	A	
4495.569....	.....	*d*	1	C	.....	.....	
4495.969....	.....	.....	3	B	.....	.....	
4504.841....	.....	*d*	1	C	.....	.....	
4514.192....	.191	.....	8	A	2	B	
4517.533....	.532	.....	11	A	4	B	
4523.406....	.....	.....	3	A	.....	.....	
4525.148....	.146	*d*?	5	A	22	A	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
4526.566....	.....	.....	1	C	.....	.....	
4528.622....	.620	c_4	29	A	29	A	
4531.155....	.155	b_3	28	A	31	A	
4531.636....	.....	*d*	2	A	.....	.....	
4537.680....	.....	.....	1	C	.....	.....	
4547.025....	.....	.....	3	B	.....	.....	
4547.853....	.853	*b*	29	A	22	A	
4549.473....	.....	.....	5	B	.....	.....	
4550.788....	.....	*d*	3	B	.....	.....	
4552.548....	.547	.....	7	B	1	C	
4556.130....	.134	*e*?	24	A	22	A	⊙ Fe–Cr
4556.942....	.....	.....	1	C	.....	.....	
4558.111....	.....	.....	1	C	.....	.....	
4560.099....	.....	*d*	1	C	.....	.....	
4566.523....	.....	.....	3	B	.....	.....	
4574.728....	.726	.....	7	B	2	B	
4581.520....	.519	*d*	3	C	2	B	
4583.838....	.....	.....	3	B	.....	.....	
4587.135....	.....	.....	4	B	.....	.....	
4592.658....	.658	.....	13	A	28	A	
4595.367....	.365	.....	5	B	1	C	
4696.069....	.....	.....	5	B	.....	.....	
4598.125....	.....	*d*	3	B	.....	.....	
4600.940....	.....	.....	2	C	.....	.....	
4602.009....	.007	.....	5	A	4	A	
4602.947....	.947	.....	17	A	39	A	
4607.659....	.657	*d*	5	A	7	A	
4611.289....	.288	*d*	5	A	14	A	
4613.212....	.214	*d*	3	B	2	B	
4614.219....	.....	.....	1	C	.....	.....	
4618.768....	.....	.....	4	A	.....	.....	
4619.297....	.297	.....	5	A	10	A	
4625.057....	.055	*d*	5	B	10	A	
4630.127....	.128	.....	5	A	10	A	
4632.917....	.918	.....	5	A	14	A	
4635.849....	.....	.....	3	B	.....	.....	
4637.516....	.513	*d*	3	B	4	A	
4638.018....	.019	*b*	18	A	6	A	
4643.471....	.471	.....	5	B	6	A	
4647.439....	.440	*b*	17	A	28	A	
4654.504....	.504	*b*	3	B	6	A	
4654.632....	.629	*d*	3	C	4	B	
4661.541....	.....	.....	1	C	.....	.....	
4661.978....	.....	.....	3	A	.....	.....	
4663.186....	.....	.....	1	C	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
4667.462	.461	*b*	5	B	14	A	
4668.144	.145	*d*	5	A	10	A	I, h
4669.177	.177	.....	5	A	2	C	I, h
4673.172	.171	.....	5	A	4	B	
4678.856	.854	.....	18	A	25	A	
4680.300	.....	.....	2	C	.....	.....	
4682.114	.....	.....	2	C	.....	.....	
4683.568	.....	.....	3	C	.....	.....	
4687.390	.....	.....	2	C	.....	.....	
4689.498	.....	.....	2	C	.....	.....	
4690.149	.....	.....	3	C	.....	.....	
4691.417	.417	.....	18	A	22	A	
4700.174	.....	*d*	1	C	.....	.....	
4701.055	.....	.....	6	C	.....	.....	
4704.962	.960	.....	7	B	1	C	I, h
4705.467	.....	?	4	C	.....	.....	
4707.283	.283	*d*	6	B	16	A	
4707.490	.....	.....	7	B	.....	.....	
4709.005	.....	*d*	5	C	.....	.....	
4710.288	.288	*b*	22	A	16	C	
4721.000	.....	.....	5	C	.....	.....	
4727.408	.....	*d*	6	B	.....	.....	
4728.	.558	.....	.....	.....	6	B	
4729.031	.....	*e*	1	C	.....	.....	
4731.404	.....	.....	6	C	.....	.....	
4733.598	.598	*a*	9	A	12	A	
4734.103	.....	.....	3	C	.....	.....	
4735.849	.....	.....	9	B	.....	.....	
4736.782	.782	*d*	7	B	20	A	
4737.636	.....	.....	4	C	.....	.....	
4740.346	.....	.....	4	B	.....	.....	
4741.084	.....	.....	3	C	.....	.....	
4741.534	.535	*b*	9	A	8	A	
4745.807	.809	*b*	4	B	6	A	
4757.585	.....	.....	7	A	.....	.....	
4771.705	.....	.....	2	C	.....	.....	
4772.818	.819	*b*	7	A	4	B	
4779.447	.....	.....	3	C	.....	.....	
4786.813	.812	*b*	28	A	12	A	
4788.760	.....	.....	6	B	.....	.....	
4789.656	.655	*b*	22	A	15	A	
4800.655	.....	.....	1	C	.....	.....	
4802.886	.....	.....	2	C	.....	.....	
4832.737	.....	.....	1	C	.....	.....	
4838.522	.....	.....	1	C	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
4839.552	.....	.....	2	C	.....	.....	
4843.158	.....	.....	2	C	.....	.....	
4855.686	.....	.....	2	C	.....	.....	
4859.750	.750	*c*5	4	A	16	A	
4863.656	.....	.....	2	C	.....	.....	
4871.327	.327	*c*5	4	B	23	A	
4872.145	.147	*c*5	3	A	18	A	
4878.220	.220	*c*5	4	A	12	A	
4881.729	.....	.....	2	C	.....	.....	
4882.154	.....	*d*	2	C	.....	.....	
4885.438	.....	.....	3	B	.....	.....	
4886.338	.....	.....	3	C	.....	.....	
4890.764	.765	*c*5	3	B	23	A	
4891.503	.501	*c*5	2	C	20	A	
4903.319	.319	*d*	4	A	10	A	I, fringes poor
4909.390	.....	?	2	C	.....	.....	
4910.030	.....	?	3	C	.....	.....	
4910.331	.....	?	2	C	.....	.....	
4910.573	.....	?	2	C	.....	.....	
4918.998	.001	*c*5	3	C	21	A	
4920.510	.513	*c*5	2	B	23	A	
4924.776	.775	*b*	16	A	2	B	
4938.820	.823	*d*	5	B	5	B	
4939.247	.....	?	1	C	.....	.....	
4939.690	.692	*a*	10	B	8	A	
4946.396	.398	*d*	6	C	1	C	
4950.115	.....	*d*	2	C	.....	.....	
4957.305	.....	*c*5	3	C	.....	.....	
4957.603	.605	*c*5	7	C	6	B	
4966.097	.099	*d*	3	B	6	A	
4967.902	.....	*c*	2	C	.....	.....	
4969.930	.....	*d*	2	C	.....	.....	
4973.111	.....	*d*	2	C	.....	.....	
4978.609	.....	*d*	2	C	.....	.....	
4982.510	.....	*d*	3	B	.....	.....	
4983.261	.....	*d*	3	B	.....	.....	
4983.858	.....	*d*	3	B	.....	.....	
4985.264	.....	*d*	3	B	.....	.....	
4985.556	.....	*d*	4	C	.....	.....	
4988.966	.....	*d*	3	C	.....	.....	
4991.280	.....	*d*	2	C	.....	.....	
4994.135	.136	*a*	50	A	10	A	
5001.873	.873	*d*	8	B	6	A	
5002.802	.....	?	3	C	.....	.....	
5005.722	.722	*d*	7	A	1	C	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
5006.129....	.128	*d*	7	A	8	A	
5007.291....	.....	*d*	4	A	.....	.....	
5012.074....	.074	*a*	6	A	23	A	
5014.952....	.953	*d*	7	B	3	B	
5018.440....	.....	.....	6	B	.....	.....	
5022.247....	.245	*d*	6	C	1	C	
5027.138....	.....	*d*	4	B	.....	.....	
5028.131....	.....	.....	7	C	.....	.....	
5041.076....	.077	*a*	24	A	6	B	
5041.761....	.760	*a*	31	A	10	A	
5049.827....	.827	*a*	30	A	14	A	
5051.640....	.640	*a*	32	A	12	A	
5065.022....	.....	*e*	1	C	.....	.....	
5068.776....	.775	*d*	4	B	5	B	
5074.759....	.....	*e*	4	B	.....	.....	
5079.228....	.....	*b*	19	A	.....	.....	
5079.744....	.....	*a*	23	B	.....	.....	
5083.344....	.343	*a*	17	B	7	A	
5097.000....	.....	*e*	1	C	.....	.....	
5098.705....	.705	*b*	42	A	3	B	
5107.454....	.....	*a*	22	A	.....	.....	
5107.647....	.....	*a*	22	A	.....	.....	
5110.415....	.416	*a*	18	A	7	A	
5123.727....	.725	*a*	20	B	5	B	
5125.132....	.131	*d*	4	C	1	C	
5127.367....	.365	*a*	21	B	4	B	
5131.477....	.....	*a*	2	C	.....	.....	
5133.696....	.692	*e*	4	C	6	B	Pole-effect extreme; I, fringes poor
5137.390....	.....	*d*	3	C	.....	.....	
5139.262....	.....	*d*	5	C	.....	.....	
5139.470....	.....	*d*	5	C	.....	.....	
5142.543....	.....	.....	3	C	.....	.....	
5142.935....	.933	*a*	21	A	1	C	
5150.846....	.844	*a*	30	A	5	B	
5151.918....	.916	*a*	18	B	4	B	
5162.290....	.290	*d*	5	C	2	B	Pole-effect extreme; I, fringes poor
5165.424....	.....	*d*	1	C	.....	.....	
5166.289....	.288	*a*	7	B	2	B	
5167.492....	.492	*a*	25	A	26	A	
5168.904....	.902	*a*	4	C	1	C	
5171.601....	.600	*a*	31	A	18	A	
5191.461....	.463	*d*	5	A	12	A	
5192.351....	.351	*d*	5	B	12	A	
5194.946....	.946	*d*	6	A	11	A	
5195.479....	.....	*e*	7	C	.....	.....	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
5198.713....	.716	*a*	4	B	4	B	
5202.340....	.341	*a*	38	A	7	A	
5204.582....	.586	*a*	2	C	1	C	Fe, Cr?
5208.601....	.605	*d*	4	B	3	C	
5215.187....	.....	*d*	4	B	.....	.....	
5216.280....	.280	*a*	35	A	3	B	
5217.397....	.....	*d*	4	C	.....	.....	
5226.870....	.....	*d*	4	B	.....	.....	
5227.192....	.194	*a*4	36	A	8	A	
5229.859....	.....	*d*	4	C	.....	.....	
5232.946....	.949	*d*5	4	B	21	A	
5242.497....	.496	*a*	17	B	3	B	
5250.652....	.652	.....	15	A	3	B	
5263.316....	.316	*d*	4	A	1	C	
5266.033....	.....	*d*	3	A	.....	.....	
5266.562....	.564	*d*5	13	C	19	A	
5269.540....	.541	*a*1	54	A	14	A	
5270.360....	.362	*a*4	4	B	19	A	
5273.381....	.....	*b*	1	C	.....	.....	
5281.800....	.800	*d*	4	B	7	A	
5283.627....	.629	*d*	4	B	9	A	
5302.	.308	*d*	.....	.....	5	A	
5307.	.367	*a*	.....	.....	3	B	
5324.186....	.188	*d*5	4	C	22	A	
5328.044....	.044	*a*1	4	A	15	A	
5328.537....	.535	*a*4	4	B	11	A	I, fringes poor
5329.996....	.....	*a*	1	C	.....	.....	
5332.906....	.904	*a*4	15	C	3	B	
5339.938....	.939	*d*5	3	B	6	A	
5341.029....	.027	*a*4	4	B	17	A	
5364.881....	.....	*e*	3	B	.....	.....	
5365.405....	.....	*a*	3	B	.....	.....	
5367.475....	.475	*e*	3	C	7	B	
5369.976....	.967	*e*	3	B	8	B	Diff.>error
5371.495....	.494	*a*1	20	A	18	A	
5379.582....	.....	*a*	1	C	.....	.....	
5383.378....	.376	*e*	3	C	15	B	
5393.179....	.176	*d*5	3	B	8	A	
5397.136....	.133	*a*4	4	B	31	A	
5400.512....	.510	*e*	3	C	1	C	
5404.149....	.144	*e*	3	B	15	B	Diff.>error
5405.780....	.780	*a*4	20	A	30	A	
5410.918....	.916	*e*	3	B	13	B	
5415.208....	.204	*e*	3	B	15	B	
5424.071....	.072	*e*	3	B	16	B	

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
5429.702....	.701	*a*4	20	A	20	A	
5434.529....	.528	*a*4	20	A	32	A	
5445.048....	.046	*e*	3	C	3	B	
5446.920....	.921	*a*4	44	A	21	A	
5455.616....	.615	*a*4	4	C	22	A	
5462.972....	.....	*e*	3	C	.....	.....	
5463.284....	.....	*e*	3	C	.....	.....	
5466.406....	.....	*d*	1	C	.....	.....	
5473.912....	.909	*d*	3	C	1	C	
5476.300....	.....	*a*4	2	C	.....	.....	
5476.573....	.574	*d*5	3	A	5	B	
5497.522....	.521	*a*3	48	A	20	A	
5501.470....	.470	*a*3	48	A	17	A	
5506.784....	.783	*a*3	48	A	21	A	
5535.419....	.....	*a*4	24	A	.....	.....	
5543.930....	.....	*d*	1	C	.....	.....	
5554.894....	.893	*e*	3	C	1	C	
5563.605....	.....	*d*	3	C	.....	.....	
5565.708....	.710	*e*	4	B	1	C	
5569.627....	.627	*d*5	3	C	20	A	
5572.849....	.851	*d*5	3	C	20	A	
5576.095....	.098	*d*5	3	C	12	A	
5586.765....	.765	*d*5	3	C	26	A	
5598.305....	.302	*e*	3	C	1	C	
5602.955....	.955	*d*5	3	C	9	A	
5615.653....	.653	*d*5	3	C	24	A	
5624.548....	.551	*d*5	3	C	17	A	
5638.269....	.269	*d*5	1	C	2	C	
5658.826....	.826	*d*5	3	C	8	A	
5662.	.523	*d*	.....	.....	5	B	
5701.	.553	?	.....	.....	2	C	
5731.	.771	?	.....	.....	2	C	
5752.	.043	?	.....	.....	1	C	
5753.	.136	*d*	.....	.....	4	B	
5775.	.090	*d*	.....	.....	2	C	
5956.	.702	*b*	.....	.....	2	C	
5975.354....	.356	*b*4	35	A	3	C	
6027.059....	.058	*b*4	35	A	10	A	
6042.	.092	*e*	.....	.....	4	B	
6065.492....	.491	*b*4	35	A	13	A	
6127.912....	.915	*b*	31	A	4	B	
6136.625....	.623	*b*4	40	A	22	A	
6136.999....	.....	*b*	26	A	.....	.....	
6137.701....	.703	*b*4	20	A	22	A	
6157.731....	.736	*b*4	31	B	10	A	Diff.>error

TABLE I—*Continued*

λ		Group	Grating		Interferometer		Remarks
Grating	Interferometer		Plates	Probable Error	Plates	Probable Error	
6165.366....	.366	*b*	36	A	3	B	
6173.342....	.344	*b*4	38	A	10	A	
6191.568....	.568	*b*4	40	A	22	A	
6200.322....	.324	*b*4	30	A	8	A	
6213.438....	.440	*b*4	40	A	18	A	
6215.	.152	*b*4	.....	.....	3	B	
6219.289....	.291	*b*4	51	A	20	A	
6230.734....	.734	*b*4	40	A	20	A	
6240.	.656	?	.....	.....	2	C	
6252.568....	.566	*b*4	40	A	21	A	
6254.268....	.267	*b*4	40	A	20	A	
6256.	.373	*b*	.....	.....	17	A	
6265.145....	.145	*b*4	40	A	20	A	
6270.	.238	*b*	.....	.....	4	B	
6280.	.627	*a*	.....	.....	9	A	
6290.	.975	*e*?	.....	.....	3	C	
6297.801....	.807	*b*4	40	B	16	B	Diff.>error
6315.312....	.319	*b*	36	B	1	C	Diff.>error
6318.028....	.029	*b*4	40	A	22	A	
6322.694....	.698	*b*	40	B	11	B	Diff.>error
6335.341....	.344	*b*4	40	A	22	A	Diff.>error
6344.159....	.162	*b*	8	B	4	B	
6355.039....	.042	*b*	16	B	9	A	
6358.	.701	?	.....	.....	7	B	
6380.	.755	*b*	.....	.....	3	C	
6393.612....	.612	*b*4	40	A	2	A	
6421.363....	.361	*b*	30	A	21	A	
6430.859....	.859	*b*4	40	A	20	A	
6462.	.738	*b*	.....	.....	7	B	
6469.	.220	?	.....	.....	1	C	
6475.	.641	*b*	.....	.....	3	B	
6494.993....	.994	*b*4	40	A	23	A	
6518.	.383	*b*	.....	.....	3	B	
6546.	.253	*b*	.....	.....	22	A	
6569.	.236	?	.....	.....	2	C	
6575.	.030	*b*	.....	.....	2	C	
6592.	.927	*b*	.....	.....	20	A	
6609.	.125	*b*	.....	.....	3	B	
6663.	.457	*b*	.....	.....	11	A	
6678.	.003	*b*4	.....	.....	21	A	
6750.	.166	*b*	.....	.....	4	B	

VI. DISCUSSION

a) *Agreement with standards.*—Eighty-three secondary standards were measured with the interferometer, of which 64 belong to groups of stable lines and 19 to groups *c*5 and *d*. For the 64 stable lines the differences, secondary standards *minus* Mount Wilson, are as follows:

0.000A for 24 lines; ±0.001A for 29; ±0.002A for 8; ±0.003A for 2; +0.004A for λ4076.

The sum of the positive differences is +0.030 A, of the negative differences A −0.025. For the 19 standards of groups *c*5 and *d* the mean difference, secondary standards *minus* Mount Wilson, is +0.007 A, a difference due to pole-effect in the sources used in the original determinations of the secondary standards. It is unfortunate that such differences are involved in the adopted secondaries. It will lead to a series of iron standards and a series of iron wave-lengths differing from each other, unless revised values based on a source measurably free from pole-effect are soon substituted for those adopted.

b) *Questioned standards.*—Questions have been raised by different observers about the lines in the subjoined list. The difficulties encountered are in the majority of cases due to the characteristics of the 6-mm, 6-amp. arc which does not produce these lines fine and sharp enough for satisfactory measurement with the interferometer. With the exception of λ 3556 and λ 4076 for which the adverse criticism is general and apparently justified by the character of the lines or of their immediate surroundings, these lines are measurable with high precision in the 12-mm, 5-amp. arc, as they then permit the use of a satisfactory order of interference.

c) *Ghosts and reversals.*—The long exposures used in the grating series to obtain the weak lines brought out ghosts of the very strong lines. These were measured and the wave-lengths of the lines calculated from the positions of the ghosts, and when possible settings were made upon the primary line, "direct measure." The gratings were made on the Rowland ruling engine, whose spacing wheel has 750 teeth. All reversals were measured and for some

lines the wave-lengths were found in all three ways. The wave-lengths from these separate determinations have been compared with the Mount Wilson interferometer wave-lengths, obtained from

	Remarks	Authority
λ 3513.....	Not sharp in 6-mm, 6-amp. arc	Bureau of Standards
	Good in 12-mm, 5-amp. arc	Mount Wilson
	Discrepancy of 0.006 A	Viefhaus*
λ 3556.....	Little wgt., poor in 6-mm, 6-amp. arc	Bureau of Standards
	Low wgt., p.e. large, shaded to red	Mount Wilson
	Meas. difficult, weak line to violet	Viefhaus
	Companion to red and violet	Goos†
λ 3677.....	Poor in 6-mm, 6-amp. arc	Bureau of Standards
	Good in 12-mm, 5-amp. arc	Mount Wilson
λ 3850.....	Not sharp in 6-mm, 6-amp. arc	Bureau of Standards
	Good in 12-mm, 5-amp. arc	Mount Wilson
λ 3865.....	Very poor in 6-mm, 6-amp. arc	Bureau of Standards
	Broad in 6-mm, 6-amp. arc	Goos
	Good in 12-mm, 5-amp. arc	Mount Wilson
λ 3906.....	Very poor in 6-mm, 6-amp. arc	Bureau of Standards
	Very discordant in grating measures	
	Good in 12-mm, 5-amp. arc	Mount Wilson
λ 4076.....	Very poor in 6-mm, 6-amp. arc	Bureau of Standards
	Poor, λ 3057 4th order coincides in 3d	Mount Wilson
	Difficult, shaded to violet and red	Viefhaus
λ 4191.....	Very poor in 6-mm, 6-amp. arc	Bureau of Standards
	d line good in 12-mm, 5-amp. arc	Mount Wilson
λ 4233.....	Very poor in 6-mm, 6-amp. arc	Bureau of Standards
	d line good in 12-mm, 5-amp. arc	Mount Wilson
λ 4736.....	No wgt. in 6-mm, 6-amp. arc	Bureau of Standards
	d line good in 12-mm, 5-amp. arc	Mount Wilson
λ 5167.....	Poor in 6-mm, 6-amp. arc	Bureau of Standards
	Good in 12-mm, 5-amp. arc	Mount Wilson
λ 5266.....	0.003A > international value, 6-mm, 6-amp. arc	Bureau of Standards
	d line good in 12-mm, 5-amp. arc	Mount Wilson
λ 5371.....	Not sharp in 6-mm, 6-amp. arc	Bureau of Standards
	Good in 12-mm, 5-amp. arc	Mount Wilson
λ 6678.....	No wgt. in 6-mm, 6-amp. arc	Bureau of Standards
	Good in 12-mm, 5-amp. arc	Mount Wilson

* *Zeitschrift für wissenschaftliche Photographie*, **13**, 209, 245, 1914.
† *Astronomische Nachrichten*, **199**, 33, 1914.

weaker exposures upon the center of a somewhat leaner arc giving very fine lines. The results of the comparisons for some threescore lines are: mean difference, ghosts *minus* interferometer, −0.0004 A, reversals *minus* interferometer, −0.0002 A, "direct measures" *minus* interferometer, +0.0020 A.

From the close agreement of the wave-lengths given by reversals and ghosts with those from the interferometer it is evident that the reversals and ghosts correspond to the lines when produced in the core of a lean arc and hence that the absorbing centers in the cooler outer vapor producing the reversals have the same period as the emitting centers in the core of the arc, and that the maximum of the line, to which the ghosts correspond, is not displaced by the strong exposure. The excess of 0.002 A given by the direct measures indicates a slight unsymmetrical widening for such over-exposed lines, in general toward the red. This characteristic renders them of doubtful utility as standards when unreversed, unless produced in a lean arc. As under special circumstances strong lines only may be available for reference, the reliability of the wave-lengths given by ghosts or reversals may prove useful.

VII. COMPARISONS WITH BUREAU OF STANDARDS

a) *Stable lines as a whole.*—Approximately 250 stable lines are common to the interferometer measures[1] of the Bureau of Standards and the Mount Wilson lists. For the Mount Wilson interferometer measures *minus* the Bureau of Standards, the sum of the positive differences is +0.187 A, the sum of the negative differences −0.162 A, the mean difference ±0.0014 A, the systematic difference +0.0001 A. For the Mount Wilson grating measures *minus* the Bureau of Standards, the sum of the positive differences is +0.202 A, the sum of the negative differences −0.184 A, the mean difference ±0.0015 A, and the systematic difference again +0.0001 A.

b) *Stable lines by spectral regions.*—From Table II it is seen that for the interferometer measures there is good agreement except in the region to the red of λ 6200. Here the Mount Wilson wave-lengths average 0.001 A longer than the measures of the Bureau of

[1] Burns, Meggers, and Merrill, *Bulletin of the Bureau of Standards*, **13**, 245, 1916.

Standards. This lack of agreement probably arises from the paucity of standards in the orange-red region and slight variations in drawing the correction-curves.

The Mount Wilson grating wave-lengths appear to be systematically too small for the region λ 3373–λ 3500 compared with both interferometer series. This, however, is due to the inclusion of a few lines showing large negative differences; and whenever the systematic difference approximates 0.001 A, it would fall well below that limit by omitting two or three lines of low weight.

c) *Unstable lines of groups c5 and d.*—There are 46 lines of groups *c*5 and *d* common to the Bureau of Standards and Mount Wilson interferometer series. For these the Bureau of Standards wave-lengths obtained with the central zone of the 6-mm, 6-amp. arc adopted at Bonn[1] are systematically longer than those made with the central zone of a 12-mm, 5-amp. arc. The average difference Bureau of Standards *minus* Mount Wilson is +0.007 A. There are 34 other lines of the same groups common to the Mount Wilson interferometer series and the grating measures by Burns.[2] For these lines the average difference Burns *minus* Mount Wilson is +0.008 A. From this it appears that the source adopted at Bonn exhibits nearly the same degree of pole-effect as the arc used originally by Burns. In their paper Burns, Meggers, and Merrill say: "The region λ 3500 A to λ 4200 A was observed with both 4 and 6 amperes, but no differences in wave-length were detected as a result of the increased current strength."[3] Unfortunately for such a test, unstable lines are relatively rare in this region, and they observed only one such line, viz., λ 4191. Of this they say[4] that it could be measured only with a low order of interference and had little weight in the final results. Their wave-length for it differs by 0.003 A from the international value. In saying that interferometer observations under the conditions used by them were found to be reasonably free from the effects of pole-shifts, they seem to have had in mind not absolute effects, but

[1] *Transactions of the International Union for Co-operation in Solar Research*, **4**, 59, 1914.

[2] *Lick Observatory Bulletin*, **8**, 27, 1913.

[3] *Loc. cit.*, p. 247. [4] *Ibid.*, p. 261.

rather that the arc used by them did not differ greatly from the average arc with which the secondary standards were originally obtained. This agrees with the Mount Wilson observations which show that the secondary standards of groups *c*5 and *d* are contaminated by pole-effect to practically the same degree as the Bureau of Standards measurements of lines of these groups. That the measurement of these lines in the 6-mm, 6-amp. arc is difficult and relatively uncertain is shown by the Bureau of Standards measures; for 12 secondary standards belonging to groups *c*5 and *d* the mean difference, Bureau of Standards *minus* International, is

TABLE II

MOUNT WILSON *minus* BUREAU OF STANDARDS BY SPECTRAL REGIONS

REGION	INTERFEROMETER		GRATING	
	Number of Lines	Systematic Difference	Number of Lines	Systematic Difference
3370–3500	23	+0.0003 A	30	−0.0013 A
3500–3600	17	0.0000	18	+0.0006
3600–3700	16	+0.0005	15	+0.0006
3700–3800	13	+0.0001	16	+0.0003
3800–3900	12	−0.0004	12	+0.0001
3900–4000	11	−0.0005	13	−0.0003
4000–4200	18	−0.0006	19	+0.0010
4200–4400	18	−0.0006	18	−0.0003
4400–4600	22	−0.0001	23	+0.0002
4600–4800	15	−0.0003	18	−0.0003
4800–5200	19	+0.0006	22	+0.0009
5200–5700	22	0.0000	24	+0.0008
6000–6200	12	−0.0001	10	−0.0011
6200–6500	24	+0.0010	17	−0.0003
6500–6750	8	+0.0010	.....	.....

+0.0012 A, while for stable standards it is 0.0000 A, and in their list of secondary standards differing by more than 0.001 A from International values, half of the lines belong to groups *c*5 and *d*, though they form only one-fifth of the total number of secondary standards.

d) *Intensity effect.*—Burns, Meggers, and Merrill were of the opinion that for lines weaker than the standards the grating gives wave-lengths different from those obtained by the interferometer, but that the wave-lengths obtained by the latter instrument are free from an intensity effect. In the present series of grating measures an effort was made to obtain as many of the weaker

lines as possible. The lines common to this series and the Bureau of Standards list have been compared in three groups, intensities 1–3, 4–5, and stronger than 6.

It is evident from results given in Table III that in the Mount Wilson grating series the wave-lengths of lines weaker than the standards show no systematic deviation from the Bureau of Standards interferometer values depending upon line-intensity. There is, moreover, no systematic difference between the Mount Wilson grating and interferometer measures for weak lines, or between the interferometer measures for strong and weak exposures.

e) *Grating and interferometer.*—As to the use of both grating and interferometer in obtaining relative wave-lengths as suggested by the American committee, we have found the practical advantage

TABLE III

BUREAU OF STANDARDS INTERFEROMETER *minus* MOUNT WILSON GRATING

	INTENSITIES					
	1–3		4–5		6 and Above	
Positive differences	+0.069	36 lines	+0.077	43 lines	+0.021	12 lines
Negative differences	−0.079	33 lines	−0.068	39 lines	−0.038	21 lines
Zero differences	0.000	17 lines	0.000	33 lines	0.000	12 lines
Mean differences	±0.0017	86 lines	±0.0013	115 lines	±0.0013	45 lines
Systematic differences	−0.0001	86 lines	+0.0001	115 lines	−0.0004	45 lines

to be the detection of accidental errors, to which attention was directed by occasional marked disagreement between the results from the two methods, rather than the elimination of complementary errors. Even with optically perfect instruments each method has in practice both advantages and disadvantages.

For the interferometer the main points of superiority are: (1) the long range of spectrum on each plate, allowing the use of many standards or the bridging of wide gaps between standards; (2) the wide variation of resolving power without loss in extent of spectrum; (3) the moderate sensibility to instrumental disturbances; and (4) the less exacting character of the necessary microscopic measurements. The disadvantages are: (1) the integrating effect introduced by diaphragms with relatively large openings in front of the etalon; (2) the loss in separation of close lines due to coincidences

and the low auxiliary dispersion usually employed; (3) the loss of light due to absorption in the metal film; and (4) the necessity of applying the correction for phase-change.

For the grating spectrograph the advantages are: (1) the easily obtained high dispersion combined with great resolution for spectral regions rich in lines; (2) the relative ease, in practice, with which faint lines may be obtained; (3) the simplicity of the instrumental equipment; and (4) the great analyzing power in forms free from astigmatism. Its disadvantages are: (1) the extreme sensitiveness to instrumental disturbances; (2) the difficulties involved in obtaining the necessary degree of perfection in the illumination; (3) the narrow spectral range under high dispersion, limiting the number of available standards; and (4) the higher precision required in the measurement of the spectrograms.

The theoretical advantages of the two instruments are well compared by Dr. Sparrow as follows:

> The defects of the gratings are fixed. If we have a good instrument we can make measurements as good as the best; if it is defective a definite limit is set to the accuracy of all our measurements. With the interferometer a good pair of plates may become defective through rotating one of them, or through tarnish or non-uniformity of the silver film; on the other hand, we may more or less average out the errors of a defective pair by this process, since each silvering or change of position makes virtually a new pair of plates.[1]

In the present investigation we have used three pairs of glass interferometer plates by Jobin and a pair of fused quartz by Hilger. The plates were several times resilvered with films of high uniformity, and were frequently changed in relative angular position. In no case was a plate used on which there appeared any evidence of tarnish or variable thickness of metal. Five high-quality gratings, two by Michelson and three by Anderson, were used in obtaining the grating series of spectrograms. As the apparent distribution of intensity in a spectral line depends upon the peculiarities of the ruling engine and the particular conditions under which each grating is produced, it is plainly an advantage in eliminating any resultant systematic errors to use gratings ruled upon two types of engine and under different circumstances for the

[1] *Astrophysical Journal*, **49**, 95, 1919.

two types. In view of the diversity of instrumental equipment employed, it is probable that defects inherent in the particular instruments, whether interferometers or gratings, play a minor rôle in both series of measures.

Moreover, the absence of systematic effects depending upon line-intensity, the precautions taken to avoid errors due to pole-effect, and the substantial agreement shown by the wave-lengths in the two series lend weight to the results. It is perhaps not too much to hope that, for lines common to our two lists and having probable errors marked A or B, the weighted mean wave-length will be found accurate to one unit in the third decimal place.

Assistance in measurement and reduction has been given by Mrs. A. H. Joy, who as Miss Burns was formerly a member of the computing division, by Miss A. M. Brayton, by Miss A. L. Miller, and by Miss L. M. Keener. For their interested co-operation and efficient work we wish to express our appreciation.

MOUNT WILSON OBSERVATORY
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ON THE ABSORPTION SPECTRUM OF HYDROGEN CHLORIDE

By WALTER F. COLBY and CHARLES F. MEYER

ABSTRACT

Hydrogen-chloride absorption band, 3.16 to 3.70 μ.—Because of the great theoretical interest attached to the absorption spectrum of HCl, the authors have undertaken to add experimental data. For most of the observations an absorption chamber 60 cm long which could be heated to incipient redness was used, since Paton had found that as the temperature is raised the number of observable lines is increased while there is no *shift due to temperature*. These results were confirmed. The mean *wave-numbers for 28 lines*, 20 of which have shorter wave-lengths than the center of the group, are given in Table I. The *law of spacing* is not parabolic, as has been supposed, but a cubic term is found to be necessary. The wave-numbers are given by the equation $\nu = 28{,}863.60 + 205.82\ n - 3.082\ n^2 - 0.0165\ n^3$, the mean difference between observed and calculated being 2. The cubic term cannot be due to overlapping of lines at the base. The results obtained by Paton at 250° C. have been reduced. An explanation of the deviations from Imes's results is suggested. Only slight evidence of the *existence of a satellite* on the long-wave-length side of each line was obtained. No compensation chamber was used in these experiments, as a direct test showed it to be superfluous.

The absorption of hydrogen chloride falls into two regions, one extending from 3.35 μ to 3.85 μ (see Fig. 1*b*), and the other from 1.73 μ to 1.83 μ (Fig. 1*a*). The second region falls at approximately twice the frequency of the first and is less intense, whence it has come to be known as the "harmonic," and the first as the "fundamental." In each region the absorption consists of numerous lines, regularly but not uniformly spaced. The only precise measurements which have been made upon these lines were made by Imes,[1] who worked with the absorbing gas at room temperature, as did previous investigators.[2]

Some work on the "fundamental" carried out by Mr. Paton,[3] with the absorbing gas at a temperature of 250° C., showed that as the temperature of the gas was raised, the individual lines retained

[1] *Astrophysical Journal*, **50**, 251, 1919.

[2] Brinsmade and Kemble, *Proceedings of the National Academy of Sciences*, **3**, 420, 1917, and Eva v. Bahr, *Verhandlungen der deutschen physikalischen Gesellschaft*, **15**, 1150, 1913.

[3] *Physical Review*, **15**, 541, 1920.

their position as nearly as could be measured, but that through a redistribution of intensities of absorption the number of observable lines was increased. This was to be expected on the basis of the rotational theory now commonly held for this type of absorption.

The absorption spectrum of hydrogen chloride is of great theoretical interest, and for this reason the authors have undertaken to add to experimental data existing upon it. The present paper deals with what has thus far been done upon the "fundamental." Certain points which are of interest have been established, but other points remain unestablished, and no work has yet been done upon the "harmonic." It is hoped to do something

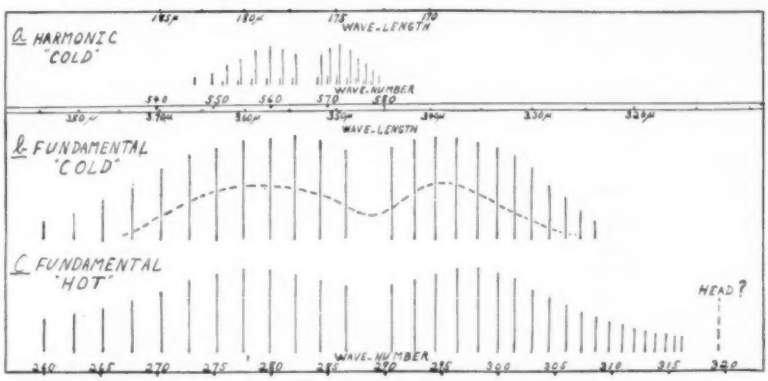


FIG. 1

more in the future with hydrogen chloride and with the other hydrogen halides.

The apparatus is similar to that used by Imes, and we have used the same 7500-line grating. The absorption chamber consists of a tube of high-temperature glass kindly furnished by the Libby Glass Company. It is 60 cm long and 8 cm in internal diameter and is provided with mica windows. Provision is made for heating electrically, and when working with the gas "hot," the tube was heated to a glow which could be just seen in a darkened room.

Some measurements have also been made with the gas "cold" (room temperature), some with the 60 cm chamber, some with

Imes's chamber 16 cm long, and some using a still shorter chamber 4 cm long.

The wave-lengths of twenty lines on the side of the center toward short wave-lengths, and eight lines on the opposite side of the center have been measured. The center is marked by the absence of one line in the otherwise regular spacing. The lines on the side of short wave-lengths were measured first, and when plotting between n, the number of the line counted from the center, and ν, the wave-number, it was possible to fit these lines so closely to a parabola that it was believed that the spacing of the entire band would be represented by a parabola. This belief

TABLE I

n	ν Measured	ν Computed	Difference	n	ν Measured	ν Computed	Difference
−8	27031.	27028.	3.	7	30148.	30148.	0.
−7	278.	277.	1.	8	300.	305.	4.
−6	520.	521.	−1.	9	453.	454.	−1.
−5	760.	760.	0.	10	597.	597.	0.
−4	991.	992.	−1.	11	732.	733.	−1.
−3	28217.	28219.	−2.	12	858.	861.	−3.
−2	437.	440.	−3.	13	984.	982.	2.
−1	652.	655.	−3.	14	31095.	31096.	−1.
1	29065.	29066.	−1.	15	198.	202.	−4.
2	265.	263.	2.	16	298.	300.	−2.
3	456.	453.	3.	17	388.	391.	−3.
4	636.	637.	−1.	18	481.	474.	7.
5	816.	814.	2.	19	554.	549.	5.
6	986.	984.	2.	20	615.	616.	−1.

was expressed in a paper given before the Physical Society at Cleveland last November. But when the eight lines on the other side were measured, it was found that these rapidly deviated from this parabola, and a little consideration made it clear that it would not be possible to fit a parabola to the entire band. The results of the measurements are given in Table I. The first column on the left gives the number of the line, which, on the side of short wave-lengths, is taken as positive and on the side of long wave-lengths is taken as negative; these will in future be referred to respectively as the positive and negative sides. The measured wave-numbers are given in the second column. The wave-numbers given throughout are "waves per decimeter." This unit is chosen

as it is convenient in this discussion, and a change of one wave per decimeter in this region means very nearly a change of one A in wave-length.

In passing out from the center on the positive side, the lines crowd more and more closely together, as can be seen in Figure 1. It was hoped that by raising the temperature of the gas sufficiently, and thus raising the absorption in the lines of higher number, it might be possible to detect a definite head to this absorption region. The existence of a head has not been established, but we hope to use still higher temperatures in the future with a view to searching for it again. The possibility of developing a head on the positive side has caused us to devote most of our attention to measurements of lines on this side. Moreover, on the negative side, after about the twelfth member, the lines fall into a region of absorption by water-vapor, and this complicates the making of measurements.

The eight lines which have been measured on the negative side, and the first eighteen of the twenty on the positive side, have been fitted to a cubic. The equation of the cubic is:

$$\nu = 28863.60 + 205.8239n - 3.081809n^2 - 0.0164817 1n^3.$$

The nineteenth and twentieth lines were not included in the computation, but they fall satisfactorily on the extrapolated curve. The values calculated according to this cubic are given in the third column of the table, and the differences between measured and calculated values are given in the fourth column.

In Figure 2, curve II, are plotted the residuals obtained after subtracting the arbitrary parabola

$$\nu' = 28880.24 + 204.271n - 3.33654n^2$$

from the cubic. The plotted points show the residuals obtained after subtracting the same parabola from the measured wave-numbers. Now if the spacing of the lines were truly parabolic, then we should still have a parabola left after subtracting a parabola, and it is evident that this is not so.

The wave-numbers given in Table I are in general not the result of a single measurement of the position of a line. On some

lines as many as six measurements were made. There were sixty-seven measurements made in all with the gas "hot," and twenty-seven made with the gas "cold." No systematic shift due to temperature has been observed and, in making up the averages of column 2 of the table, fourteen measurements with the gas "cold" were included. Something more will be said below regarding "cold" measurements.

The above-mentioned parabola has also been subtracted out of Imes's measured wave-numbers and the residuals have been plotted. Figure 2, I, is a smooth curve going through these points: the points themselves have been omitted to avoid confusion of

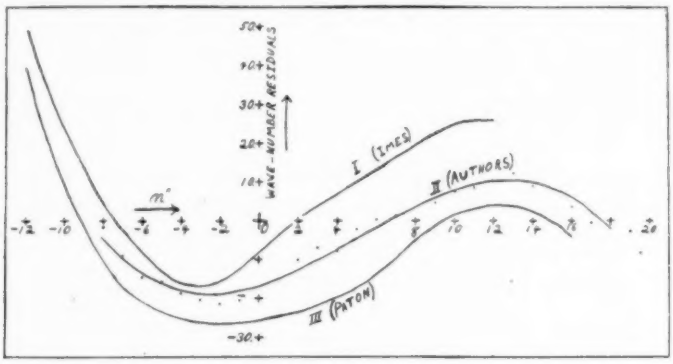


FIG. 2

the diagram. It will be noted that the differences between Imes's values and our own are rather large on the positive side, and this we measured first. We spent much time in trying to reconcile the two sets of data, and at first believed that some systematic error had crept into one set of determinations or the other. A somewhat faulty determination of the spectrometer constant may account for a portion of the differences. The spectrometer constant is determinable to about 0.007 per cent, so that two faulty determinations in opposite directions might account for four units. Again, a faulty determination of the position of the central image of the grating is to be considered. Our practice in determining the position of the central image has been to pass the central image over the thermopile slit, making settings every half-minute of arc,

and taking galvanometer readings at each setting. The intensity of the beam of infra-red radiation is cut down in this case by placing a piece of tissue paper across the beam just before it enters the first slit of the spectroscope; otherwise the galvanometer would go off the scale. The positions of the central image determined in this way have been checked by making five measurements upon absorption lines with the grating turned first to one side of the normal and then to the other. In every determination the check was quite satisfactory. On the other hand, Imes determined the position of the central image visually and did not make any very careful check upon the visual method as applied to his thermopile, and as it frequently happens that the true position of the central image differs slightly from the one visually determined, it may be that some error has crept into his results from this source. But the entire differences between his values and ours cannot be satisfactorily explained as experimental error.

There is probably a real shift in Imes's determinations as compared to ours. There are several causes which may be operative in producing shifts. In the first place, there is the slope of the continuous background which is very marked in Imes's curves. In Figure 1*b*, the waved broken line represents this continuous absorption. It is absorption between the lines due to overlapping at the base. If we consider the sixth line, then the fifth and seventh overlap with it at the base, and as the fifth is a more intense line than the seventh it will overlap more, and there will be a shift toward the fifth line. The magnitude of this shift for a given line will depend upon the numbers of molecules causing absorption in the adjacent lines, and these numbers depend upon the mass of gas in the path, and upon the temperature which affects the distribution of rotational velocities. The mass of gas in the 60 cm chamber "hot" would be about four-thirds that in the Imes chamber, since the chamber is four times as long and the absolute temperature is about three times that of the gas "cold." But the temperature distributes the rotational velocities more evenly, so that the slope of the continuous background is less steep in the 60 cm chamber.

Secondly, it may well be that the absorption lines thus far observed in the "fundamental" do not represent the ultimate structure of the absorption. In the "harmonic" a faint satellite was observed by Imes on the side of long wave-lengths of the more prominent members, Figure 1*a*. The satellite has been explained by Loomis[1] as being due to an isotope of chlorine, and if this explanation is correct it should also be present in the "fundamental." But our definition may be just insufficient to detect it, and the measurements may give the position of a composite of the strong line and this satellite. The position of maximum absorption for this composite would, on account of the exponential law of absorption, shift somewhat with varying numbers of molecules taking part in the absorption, though the ratio of the number of molecules affecting the strong line and the satellite may be supposed constant under all conditions.

Shifts due to overlapping and due to the satellite would affect the law of spacing. But consideration makes it clear that the elimination of the effect of overlapping cannot change the law into a parabola, and we have experimental evidence that it does not. It is somewhat premature to speculate upon the effect of elimination of shift due to the hypothetical satellites, as they may be spaced differently than Loomis supposes.

The accepted formula for absorption bands in this region is of a parabolic type

$$\nu = c_0 \pm c_1 n + c_2 n^2$$

either by the Bjerrum postulate or by the more recent and more satisfactory theory of Sommerfeld-Lenz. In both theories c_0 is dependent on the atomic vibration-frequency and is by far the largest contribution of the three terms. Loomis has pointed out that in the case of HCl the heavier isotope of Cl will produce a satellite with a ratio of frequency 1330/1331 to the predominant line. This ratio is the square root of the ratio of the reduced masses and affects c_0. As an extension of this idea one would likewise expect a variation of c_1: there would be not simply a series of equally spaced doublets, but the separation would grow with

[1] *Astrophysical Journal*, **52**, 248, 1920.

order on the positive side and decrease with order on the negative side. The effect on c_1 is due to a difference in the moments of inertia. The contributions of this term would therefore have a ratio of 1330/1332, the ratio of the reduced masses. The term itself, however, is of a lower order than the first and we could only hope to detect its contribution in the case of the higher values of n. The separation due to c_0 is 21.7, and that due to c_1 is 6.3 for $n = +20$. Together they produce a separation of 28.

A word should be said regarding the possibility of shift due to temperature. None is to be expected theoretically, and none has been observed, but individual measurements of a line frequently differ by eight or ten units and sometimes by larger amounts. It would be necessary to measure a given line or lines a number of times "cold" and a number of times "hot," and under conditions especially chosen to avoid all possibility of shift from the two causes mentioned above, before one could conclude that there is no shift as great as three or four units due to temperature. The measurements with the 60 cm chamber "cold" probably fulfilled these conditions approximately. They were made in the very beginning of our work as preliminary measurements. We at that time drew off gas from the chamber by means of an aspirator to prevent it from escaping into the room, and drew air from the room into the chamber so that it was by no means filled with gas.

Four lines on the negative side have been measured "cold" with Imes's chamber. The wave-numbers agree closely with Imes's values. We have not undertaken to map the entire region in this way as the labor involved would be considerable and would show nothing of great value. The measurements which were made "cold" with the 4 cm chamber agree very closely with the "hot" measurements with the 60 cm chamber.

Mr. Paton has kindly put at our disposal the full data which he obtained. These had never been worked up with care, as no reliable determination of the spectrometer constant was made, and the temperature of the grating was not recorded. The data are nevertheless valuable in several respects. Mr. Paton's "hot" curve was made at 250° C., with a chamber 6 cm long; thus the continuous spectrum in his curve is practically absent. We have

computed wave-numbers from his data, using an arbitrary spectrometer constant to throw the wave-numbers into the right region, and have then subtracted the same parabola. Figure 2, III, is a smooth curve drawn through the points, the points themselves being omitted. It is clear that the law of spacing is still not a parabola.

The absorption-curves of a number of the lines in this set of data show a slight asymmetry which is suggestive of a satellite on the side of long wave-lengths. The degree of asymmetry lies within the experimental error of the determination of the absorption percentage, so it is not surprising that some lines should show an asymmetry on the other side. Of twenty-three lines in which the absorption percentage rises above 30 per

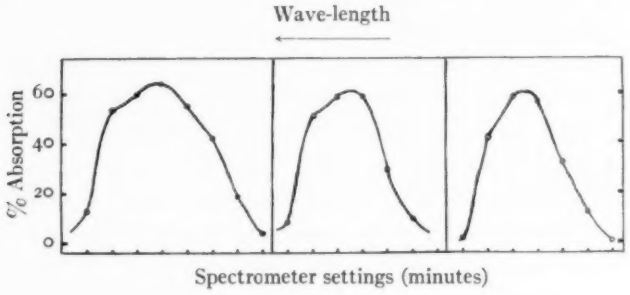


FIG. 3

cent, twelve lines show the asymmetry on the side of long wave-lengths, eight are symmetrical, two are irregular on both sides, and one shows the asymmetry on the other side. In Figure 3 are reproduced the absorption curves which show it most pronouncedly. The evidence is of course very slight. We had searched for the satellite, using a narrow slit-width, 0.25 mm, whereas most of our work has been done with a slit-width of 0.40 mm, and Imes and Paton used about 0.50 mm. We did not find the satellite. The galvanometer deflections were very small and the errors in absorption percentage correspondingly great, and it is possible, too, that the column of gas was too long and that the satellite, if it exists, was merged into the principal line.

The question has occasionally arisen whether accuracy in determinations of wave-numbers is to be gained by using a

compensating chamber; that is, by observing galvanometer deflections first with the beam passing through the absorption chamber, and then with the beam passing through a chamber of equal length containing dried air. We did not use a compensating chamber in our work, but located absorption maxima directly from the curve of deflections. By way of comparison of the two methods, we have plotted from one of Mr. Paton's sets of data first the curve of deflections and then the curve of absorption percentage obtained from the deflections through the compensating chamber. The position of every absorption maximum on the two curves is practically identical.

UNIVERSITY OF MICHIGAN
January 1921

THE EXCEPTIONALLY HIGH SOLAR PROMINENCE OF OCTOBER 8, 1920

By OLIVER J. LEE

ABSTRACT

Solar prominence of October 8, 1920.—Fifty-seven photographs were obtained, covering the various stages of the growth and gradual breaking up and final disappearance of this prominence, which attained the record height of 831,000 km. The changes are described in detail with the help of 7 photographs and 6 plots. The superstructure rose slowly at first until coherence with the base was partly broken, when the velocity suddenly changed to a much higher value, which was maintained until a more complete break was accompanied by another sudden increase. The motion of other parts was quite complex, some material returning to the sun, while other parts seemed to be attracted to points outside the sun. Electrostatic forces may have been acting, but it is not understood how. The prominence was associated with no sun-spot and seemed to be a new eruption. The H line of calcium was used in making the spectroheliograms.

The first photograph of this prominence was taken at G.M.T. 3^h5^m, October 8, through a thick haze with scattered clouds. The topheavy appearance of the eruption suggested that it might show changes, and it was followed throughout the day in spite of the unfavorable conditions. Until local noon twenty-six photographs had been taken at various intervals, and it was evident that the top of the structure was about to be separated from the base. It was therefore followed until G.M.T. 8^h33^m, when the last vestiges of it are seen at an elevation above the solar limb of 831,000 km or more than 19 minutes of arc. A fresh breeze blew directly into the dome all day, and the resulting oscillation of the telescope is all too much in evidence on many of the photographs. At no time was the prominence strong, and it was a matter of surprise to find the faint structure of the prominence recorded as the plates were developed. Fifty-seven photographs were obtained during the day.

The eruption took place on the east limb of the sun in latitude 24° south and longitude 266°. Photographs of the disk with the H line of calcium are available for the next few days, but they give no evidence of disturbance at this point beyond a few floccular specks. The nearest spot is perhaps 40 or more degrees away. On

PLATE V

Fig. 1 Fig. 4 Fig. 5

Fig. 1

Fig. 2

Fig. 3

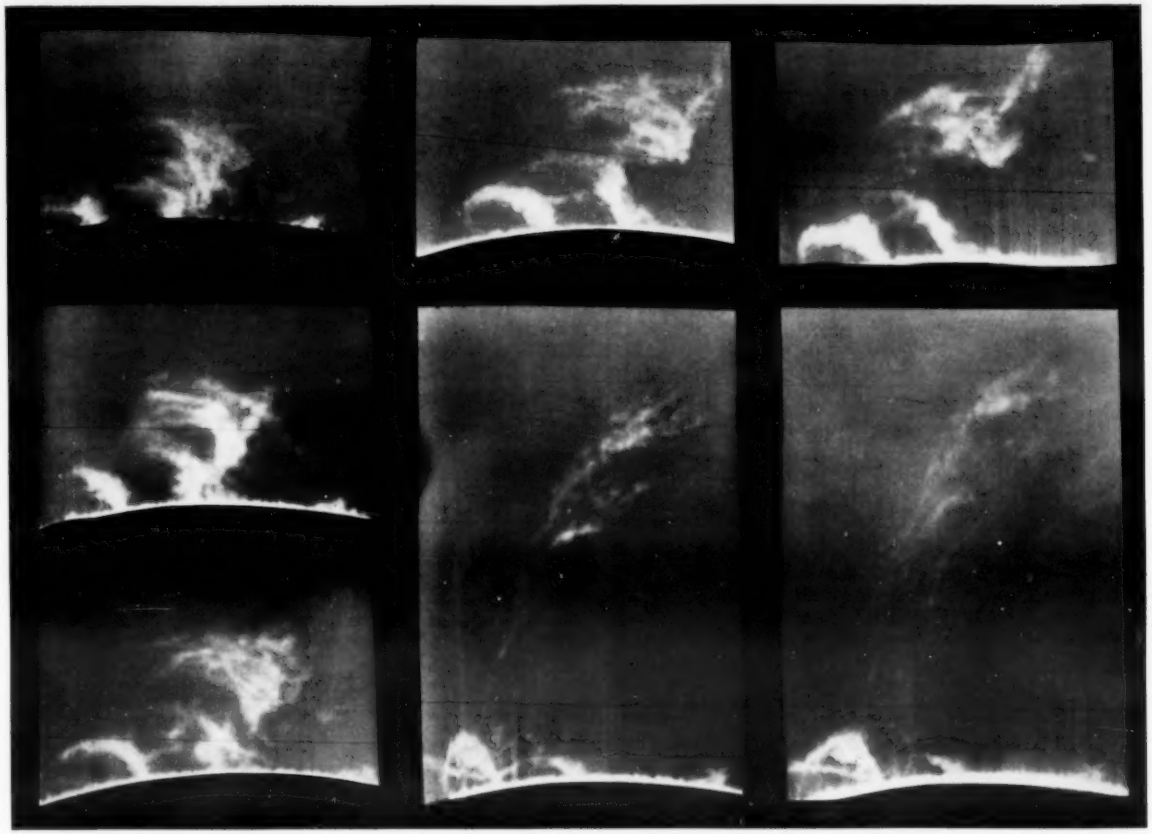


Fig. 3 Fig. 6 Fig. 7

SOLAR PROMINENCE OF OCTOBER 8, 1920

FIG. 1—3^h32^m G.M.T. FIG. 3—6^h24^m G.M.T. FIG. 5—7^h17^m G.M.T. FIG. 7—7^h54^m G.M.T.
FIG. 2—5^h43^m G.M.T. FIG. 4—6^h59^m G.M.T. FIG. 6—7^h50^m G.M.T.

the previous day a low diffuse prominence overlay this region, but its form had nothing in common with the first photographs made on October 8. This circumstance, taken with the fact that new matter was being shot up into the base of the prominence during its development, indicates that the latter was a new eruption.

In the diagram the plot *A* exhibits the vertical ascent of the crest or top of the prominence. It was not possible to derive a similar plot for the under side of the prominence, the changes in form being too radical. In the first section of plot *A* the crosses in each case represent the mean height of from two to five photographs taken in quick succession. After the changes became more rapid, as shown in the second and third parts of this plot, it became more difficult to set on the faint traces of matter forming the top of the crest. In all the plots given in the figure the numbers are the velocities in kilometers per second.

Plot *A* is made up of three straight lines. While instantaneous increases in velocity are indicated, the times of observation and the scale of the plot do not preclude the possibility that the change occupied several minutes. There can be no doubt that in each interval of time the velocity of ascent is constant. From a study of twenty-four eruptive prominences, Pettit[1] has established that the velocities of ascent in prominences receive impulsive increments of speed, and that between these moments of increase the velocities are constant.

The accompanying plate exhibits some of the most striking changes of form. No attempt has been made to reproduce the last stages photographed.

Considerable difficulty was experienced in measuring the velocities of different parts in the early forms. The masses are too irregular and diffuse. About eighty determinations of velocity were made with the "blink" comparator on thirty-seven points. The individual velocities are of course rather discordant. Directions of motion are more satisfactory and give a fairly good indication of how the main body of the prominence became detached from the base. The five smaller cuts show how this took place.

[1] *Astrophysical Journal*, **50**, 206, 1919; *Publications of the Yerkes Observatory*, Vol. III, Part IV, probably will appear in 1921.

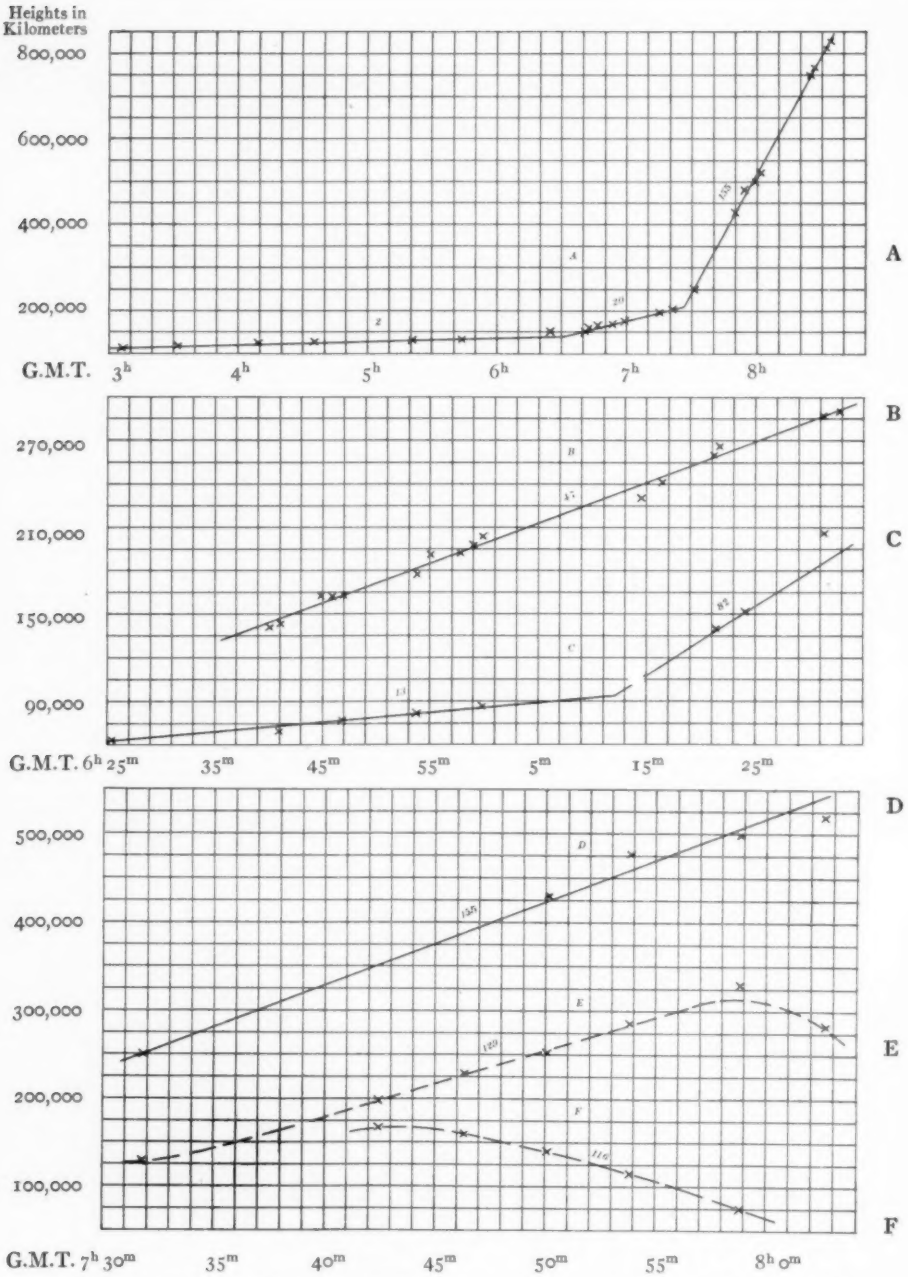


DIAGRAM 1.—Heights and velocities of *A*, the crest; *B*, the secondary eruption from the head; *C*, the isolated cloudlet at the right; *D*, the crest for comparison with *E* and *F*; *E*, the large, dense condensation near the bottom of the ascending head; *F*, the small bright knot approaching the horn prominence.

During the first interval of observation the superstructure was slowly rising. The greatest velocities during this period were in the streamers toward the left, the largest being 77 km per second. The objective of these arms seemed to be some point of attraction outside the lower left-hand corner of the figures, as indicated in the first photograph. Then the low hornlike prominence at the left became the more powerful and grew in size and brightness with the stream of matter fed to it by the main eruption and other matter coming up into it from the limb of the sun itself. The branches projecting from time to time higher up seemed variously affected by the attraction of the horn and the point at its left and, once detached from the main mass, moved outward and up or down with velocities ranging from 14 to 26 km per second. Between the stages shown in the first two figures the straggling material between the base and head was drawn off to the left, while on the right it settled down toward the limb of the sun at the rate of a very few kilometers per second. The resulting cleavage is well shown in the photograph taken at G.M.T. 6^h24^m, although the roughly parallel lines from between which the matter was drawn are clearly seen much earlier in the series. The denser connected masses in the main head resisted this action and began ascent with increased speed. The rapid rise of the secondary eruption in the upper right-hand corner of the head is shown separately in plot *B*. The break in cohesion between this part and the rest of the head is indicated in the second figure and took place in a manner analogous to that described above. During its separation from the head it experienced for a while a slight swaying motion toward the right, southward. Then after the second large increase in velocity upward it lost its form and dissipated rapidly. The northward parts of the head proved most refractory and had swayed back toward the north several degrees of latitude when the greatest height was attained. At G.M.T. 8^h27^m the crest is still quite conspicuous. On the photographs taken at G.M.T. $8^h31^m53^s$ and $8^h33^m27^s$ the remnant is so faint that had there been but one plate no claim to an unequaled record of altitude could have been made. As it is, the last two exposures corroborate each other perfectly.

The absence of any accurate information about the component of velocity in the line of sight and of perspective in prominences makes a discussion of motions difficult, and phenomena are not always what they seem. In the stage shown in Figure 3, taken at G.M.T. 6^h24^m, a small spike projects upward from the base across the open space toward the detached mass. This body broke loose from its apparent base, traversed the open space at a velocity varying from 13 to 30 km per second, and joined the receding mass. Transfer of other material across this space is clearly seen also in the next two figures.

The small cloudlet seen widely separated toward the right was followed for nearly one hour. At G.M.T. $5^h42^m49^s$ it is a nucleus in the arm projecting downward from the right of the main head. The next figure shows it detached and strengthened by accretion. Measurement along a solar radius of nine photographs gives the points in plot *C*. The last image was indistinct and the measure of it was not given any weight in plotting. The rest indicate two periods of constant velocity connected by a short interval of change. The velocities themselves and the times of change are seen to be independent of those of the main mass. Micrometric measures in rectangular co-ordinates show that this knot at first moved away from the head at an angle of 34° with the tangent to the limb; then it changed direction to an angle of 65°, but did not get its increase in speed for another 10 to 12 minutes.

Another feature of the eruption is shown in the last group of plots. It concerns the separation of the parts of the head, the crest stubbornly resisting disruption and continuing its dash to the greatest height so far recorded, while other parts singly or in groups deserted and vanished or started back to the sun. The process continued for sometime but reached a climax when the crest had attained an altitude of 450,000 km above the limb. One small knot started back earlier and was beautifully recorded on five photographs. Two intermediate stages are shown in Figures 6 and 7. Plot *F* refers to this knot. It took a straight course with constant velocity for the top of the horn prominence, the fifth exposure showing it almost in contact. The horn itself, which had

persisted for five hours of observation with only minor changes in form, at this time exploded, shooting streamers toward the left and weakening. About fifteen minutes earlier the stump of the main prominence had discharged itself into the horn and now only an insignificant knob remained.

Plot *E* refers to the motions of a large dense mass probably coming from the lower right portion of the head. After sharing the ascending motion it finally slid into the course taken by material returning to the sun. The reversal of motion of this mass is shown. There may be later traces of it but certain identification is not possible. Plot *D* shows the altitudes of the crest during this period for comparison.

The study of this prominence elicits the following remarks:

1. Motions in this and similar prominences must be due to the interplay of many forces.

2. While this eruption took place, the parts farthest from the horn prominence and the nearby point of attraction have moved with the greater freedom.

3. So long as there was continuity of material in base and head only a very gradual rising motion took place. Once cohesion was broken, in this case by the clearing of a lane across the neck, more rapid ascent began.

4. The first increase in velocity followed the partial break shown in the third figure. The second increase came just after the more complete break seen in the fifth.

5. A center of attraction existed at some point not far to the left of the horn prominence.

6. Apparently a differentiation took place in the ascending mass so that part of it continued upward and other parts were drawn back to the sun. This is not due to the presence of different elements, since the spectroheliograph in this adjustment will record only the monochromatic radiation of the H line of calcium. Is it due to change in polarity of the crest or transfer of charge from it to its neighbor? How can this affect the motion of the appendages and not also the motion of the crest, which remains constant, as shown by its plot of altitudes? Or, can it be that breaks in the

cohesion of material amount to interrupting the paths in which transfer of charge takes place with the result of sudden change in repulsive force?

7. The base of the prominence discharged violently into the horn at the time when the crest shed its appendages. The simultaneous dissipation of widely separated parts of an eruption has been noted by Evershed.[1] Does this indicate a local field, having particular properties, surrounding this complete operation? If so, the field is not one connected with spots or a marked floccular area. It may be the field lying between sun-spot fields and having, in a fashion, complementary properties.

8. The dense part of the horn is the goal of material returning to the sun from above in a funnel-shaped path. Why should not this material rather seek the point at the left? Particularly so since the horn itself "blew up" and discharged its substance furiously toward this point only a short time later?

9. The slow development of the structure for the first hours of observation indicate a growth rather than a sudden eruption. At the rate of rise found for the first period of observation, 1.9 km per second, the prominence could have grown from the limb of the sun up to the altitude first observed in less than ten and a half hours.

10. The smaller types of jetlike ejections from the limbs of the sun are apparently real eruptions. It is more than likely that the large structures, which attain high altitudes, grow out rather leisurely and finally suffer violent disruption because of internal mechanical changes coupled with static conditions in the solar atmosphere.

YERKES OBSERVATORY
December 14, 1920

[1] *Bulletin No. LV*, Kodaikanal Observatory, 1917.

SUSPECTED VARIABLE, BOND 624, IN TRAPEZIUM OF ORION

By J. A. PARKHURST

ABSTRACT

Variability of Bond 624 in Orion.—The photo-visual magnitudes obtained from 67 plates covering the past 16 years have been arranged in order of phase according to Hartwig's elements, but no periodic variation from the mean, $8^{M}.32$, is shown and the average deviation of the normal point is only $0^{M}.06$. The comparison stars used gave excellent standards for the detection of any variation, even slight. Evidently the elements given by Hartwig cannot be correct.

Photo-visual magnitudes of seven stars in Orion, Bond 619, 628, 640, 685, 708, 734, and 741 are given and compared with Graff's values.

Hartwig has published in *Vierteljahrsschrift der Astronomischen Gesellschaft*, **55**, 220, 1920, the following elements of minimum

G. M. T.
1919 August 28, J. D. $2422199.576+6^{d}.4754$ E.

An ephemeris based on these elements also appeared in *Astronomische Nachrichten*, **212**, 231, 1920. These publications led me to arrange the plates taken with the Yerkes 40-inch refractor in order of phase according to Hartwig's elements, in search for photographic evidence of variation.

These plates were taken through a yellow filter and therefore give photo-visual magnitudes, which agree very closely with visual observations in ordinary fields. The results of a preliminary examination of 103 plates taken between 1900, September 20, and 1919, March 19, were published in *Popular Astronomy*, **27**, 578, November 1919.

Most of the plates had exposures of one to two hours and on many of them the bright stars of the trapezium with the surrounding nebulosity were too large and dense for accurate measures. Such plates were either excluded from the following list, or, if included on account of phase-value near predicted minimum, were given half weight. On plates with exposures of 5 to 50 minutes, the images of the trapezium stars were small enough to permit measurement with an artificial scale in the Hartmann microphotometer.

The system of standard magnitudes was determined by such measures of plates taken with objective-gratings, giving the following system, and the comparison with Graff's visual magnitudes.

The systematic difference, Parkhurst minus Graff, for the mean of seven stars is $+0^{M}06$. The difference for θ_2 = Bond 685, Graff's basis, is $+0^{M}02$. The individual differences are large; negative for stars in the dense nebulosity near the trapezium, and positive for stars in less nebulosity.

TABLE I

Star	Plate						Mean	Graff	Diff. P.–G.
	358	359	362	399	401	402			
Bond 619.....	$6^{M}86$	$6^{M}70$	$6^{M}72$	$6^{M}69$	$7^{M}04$	$6^{M}84$	$6^{M}78$	$7^{M}19$	$-0^{M}41$
628.....	5.22	5.16	4.92	5.23	5.14	.....	5.18	5.42	−0.24
640.....	6.84	6.71	6.74	6.55	7.04	6.78	6.73	6.83	−0.10
θ_2=685.....	5.22	5.18	4.98	5.23	5.14	.....	5.19	5.17	+0.02
708.....	6.60	6.60	6.56	6.58	6.56	6.55	6.58	6.41	+0.17
734.....	7.10	7.04	6.80	7.00	7.47	.....	7.07	6.64	+0.43
741.....	9.09	8.67	8.39	8.53	9.01	8.20	8.52	7.97	+0.55
Means.....	.....	.....	.....	.....	.....	.....	6.58	6.52	.....

On such plates of exposures less than 30^{m}, taken with or without the objective grating, the nebulosity is not troublesome and the star-images can be measured with considerable precision. When the exposure was an hour or more it was only possible to estimate the magnitudes somewhat roughly, such results being marked (:) in the list and given half weight. But even on these plates a change of half a magnitude would be quite noticeable. The best of the plates used, about one-third the total number, are quite free from the uncertainties encountered in visual comparisons on the bright, shifting background of nebulosity; the photographic results should therefore have relatively greater weight.

The results of measurements of 67 plates are given in Table II, for which the headings of the columns are self-explanatory. The plates were grouped in order of phase after minimum according to Hartwig's elements. The average magnitude of Bond 624 is 8.32,

TABLE II

NORMAL POINTS

PLATE NO.	CAL. DATE	JULIAN DAY 24	PHASE	MAG.	MEAN	
					Phase	Mag.
401	1921 Jan. 27	22717.653	0d04	8.18		
57	1909 Apr. 1	18398.583	0.1	8.25:		
65	1911 Jan. 28	19065.601	0.1	8.00		
365	1919 Dec. 3	22296.810	0.1	8.5 :		
61	1910 Feb. 19	18722.546	0.2	8.25:	0.15	8.32
18	1906 Jan. 28	17596.628	0.2	8.5 :		
339	1917 Dec. 25	21953.732	0.22	8.5 :		
22	1906 Feb. 10	17252.625	0.22	8.5 :		
72	1911 Dec. 5	19376.730	0.24	8.25:		
73	1911 Dec. 18	19389.745	0.3	8.25:		
90	1914 Feb. 15	20179.627	0.37	8.5 :		
138	1914 Nov. 1	20438.800	0.52	8.25:		
80	1912 Mar. 5	19467.552	0.58	8.5 :		
66	1911 Feb. 4	19072.623	0.6	8.5 :	0.56	8.30
26	1906 Oct. 21	17505.587	0.6	8.10		
20	1906 Feb. 4	17246.625	0.73	8.32		
70	1911 Nov. 29	19370.773	0.76	8.00:		
69	1911 Oct. 28	19338.572	0.94	8.25:		
86	1913 Jan. 23	19791.707	0.96	8.25:		
56	1909 Mar. 20	18386.595	1.0	8.25:		
143	1914 Nov. 21	20458.817	1.10	8.31	1.07	8.33
202	1916 Jan. 16	20879.713	1.13	8.5 :		
302	1917 Dec. 9	21572.754	1.28	8.4 :		
150	1914 Dec. 24	20491.724	1.64	8.25:		
67	1911 Feb. 18	19086.583	1.7	8.30		
50	1908 Feb. 20	17992.543	1.8	8.20		
304	1917 Dec. 16	21579.773	1.83	8.5 :	1.86	8.36
87	1913 Feb. 6	19805.670	1.97	8.5 :		
48	1908 Dec. 25	17966.675	2.0	8.20		
75	1912 Jan. 8	19410.740	2.06	8.5 :		
13	1905 Dec. 16	17196.691	2.49	8.5 :		
30	1907 Feb. 10	17617.568	2.5	8.5 :		
59	1909 Dec. 25	18666.712	2.6	8.5 :		
51	1908 Oct. 17	18232.906	2.7	8.30	2.67	8.36
71	1911 Dec. 1	19372.715	2.71	8.25		
23	1906 Mar. 17	17287.585	2.8	8.5 :		
198	1915 Nov. 14	20816.772	2.93	8.25:		
203	1916 Feb. 13	20907.659	3.17	8.25:		
49	1908 Feb. 2	17974.579	3.5	8.25:		
402	1921 Feb. 19	22740.576	3.57	8.02		
402	1921 Feb. 19	22740.606	3.61	8.11	3.56	8.23
336	1918 Nov. 13	21911.800	3.61	8.25		
25	1906 Mar. 31	17301.581	3.9	8.5 :		

TABLE II—*Continued*

Plate No.	Cal. Date	Julian Day 24	Phase	Mag.	Mean Phase	Mean Mag.
200	1916 Jan. 6	20869.700	4d06	8.25:		
42	1907 Dec. 1	17910.712	4.3	8.25:		
54	1909 Feb. 6	18344.566	4.3	8.5 :		
91	1914 Feb. 19	20183.585	4.33	8.25:		
355	1919 Nov. 5	22268.800	4.47	8.20		
397	1921 Jan. 12	22702.719	4.53	8.26		
159	1915 Feb. 17	20546.587	4.69	8.25:	4.57	8.28
44	1908 Jan. 2	17943.612	4.8	8.25		
68	1911 Apr. 1	19128.584	4.87	8.25		
92	1914 Feb. 26	20190.596	4.87	8.40		
358	1919 Nov. 12	22275.758	4.95	8.30		
359	1919 Nov. 12	22275.772	4.97	8.23		
360	1919 Nov. 12	22275.811	5.00	8.0 :		
246	1917 Jan. 23	21252.719	5.03	8.0 :		
311	1918 Feb. 3	21628.725	5.46	8.25:		
362	1919 Nov. 19	22282.779	5.49	8.20		
363	1919 Nov. 19	22282.821	5.54	8.25:	5.48	8.19
399	1921 Jan. 26	22716.703	5.56	8.09		
81	1912 Apr. 5	19498.573	5.70	8.25:		
338	1918 Dec. 11	21939.808	5.73	8.5 :		
234	1916 Oct. 25	21162.809	5.76	8.25:		
37	1906 Oct. 4	17853.911	5.8	8.5		
52	1908 Nov. 28	18274.774	5.8	8.5 :		
89	1914 Feb. 14	20178.609	5.82	8.5 :		
93	1914 Mar. 12	20204.580	5.89	8.25:		
64	1911 Jan. 21	19058.636	6.0	8.25:		
60	1910 Jan. 30	18702.704	6.20	8.5 :	6.09	8.44
301	1917 Nov. 18	21551.765	6.20	8.5 :		
309	1918 Jan. 9	21603.643	6.27	8.25:		
343	1919 Mar. 19	22037.579	6.37	8.5 :		
55	1909 Mar. 6	18372.576	6.47	8.5 :		

the deviations of the normal points from the mean range from $0^{M}.00$ to $0^{M}.13$ with an average value of $0^{M}.06$.

No evidence of variation of Bond 624 can be found from these plates covering the past sixteen years. The plates taken between 1919 and 1921 indicate that the elements cannot be correct, but the possibility remains that the exposures may have avoided the minima corresponding to somewhat different elements.

Figures 1, 2, and 3, which are reproductions of photographs, will give a fair idea of the appearance of the images, and of the possibility of accurate measures. They also show that the nebulosity does not affect short exposures enough to introduce errors in the results.

Figure 1 reproduces the central part of Plate O,362 taken 1919, November 19, with grating P6 and an exposure of 10 minutes. The scale is small enough to include the trapezium and also the

FIG. 1.—Negative O, 362

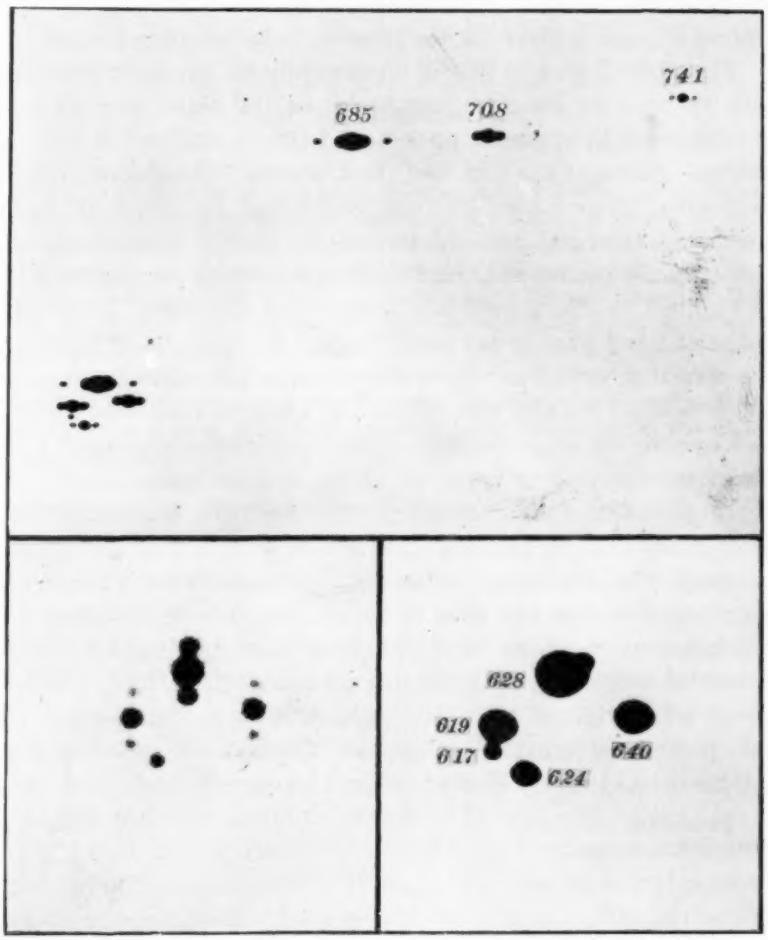


FIG. 3.—Negative O, 401

FIG. 2.—Negative O, 48

line of three stars, Bond 685, 708, and 741. Figure 2, which is a reproduction of O,48 taken 1908, January 25, with an exposure of 20 minutes, shows the trapezium on a sufficiently large scale to

hold the Bond numbers in the vicinity of the five brightest stars. Overlapping the image of 628 will be seen part of the image of Bond 633, sometimes called the sixth star in the trapezium. Figure 3 reproduces the central part of Plate O,401 taken 1921, January 27, at 15^h40^m G.M.T., with an exposure of 10 minutes, through grating P6, and is given for the purpose to be mentioned later.

Figure 1 will give an idea of the possibility of accurate measures, with an absolute scale of magnitudes on the plate, derived from the difference in apparent magnitude between the central and the spectral images of the first and third orders. These constants for the grating P6 have been carefully determined, giving the difference between central and first order spectrum as 2.38 magnitudes, and that between central and third order spectrum as 5.03 magnitudes. In Figure 1 it will be seen at a glance that the size of the central image of Bond 624 lies between the central and spectral images of the stars 619 and 640. It is also comparable with the spectral image of Bond 708 and with the central image of Bond 741. These four comparison stars therefore give us excellent standards for the detection of any variation, even slight, in Bond 624.

In *Astronomische Nachrichten*, **212,** 383, 1921, Hartwig reports a minimum for 1921, January 14, at $9^h \pm$ G.M.T. This corresponds to epoch 78. The next minimum which could be observed in this longitude was the second following, epoch 80. Plate 0,401 was taken at epoch 80 with the phase value of 0.04 days. The measured magnitude of Bond 624 on this plate is 8.18, which is about 0^M1 brighter than the mean. No confirmation of the variation can be found from this plate, which shows, moreover, that the elements given by Hartwig cannot be correct.

YERKES OBSERVATORY
March 1921

Minor Contributions and Notes

USE OF A LIME CATHODE OF CARBON IN SPECTROSCOPY

ABSTRACT

Lime cathode of carbon may be prepared by soaking a thin hard carbon strip, such as may be cut from a telephone diaphragm, in a solution of calcium and barium nitrate and then drying it. By heating this cathode in a vacuum and applying a potential difference of a few hundred volts between it and a nearby anode, an electronic current of several amperes per cm² may be obtained which may be used for *melting small quantities of highly refractory substances* or for exciting intense light from the anode metal. *This new and powerful source of line spectra* is so intense that the structure of the spectrum lines of such metals as Cd, Bi, and Pb may be studied with an echelon grating or a Lummer-Gehrcke plate. The life of the strip was usually long enough, about 20 or 30 minutes, to outlast the anode material, which was placed in a small silica tube.

Structure of bismuth lines.—Photographs made with a Lummer-Gehrcke plate and a spectrograph show the structure of lines λλ 4722, 4308, 4122, 3596, 3511, and 3397. No measurements are given.

It is well known, that calcium or barium oxide coated on a strip of platinum foil and heated red hot, sends out a large number of electrons, which may be used with advantage for melting small quantities of highly refractory substances in vacuum or for exciting intense light from metals.

The so-called Wehnelt cathode was successfully employed by Janicki,[1] Wali-Mohammed,[2] Takamine,[3] King,[4] and others in spectroscopy, for obtaining sharply defined spectral lines.

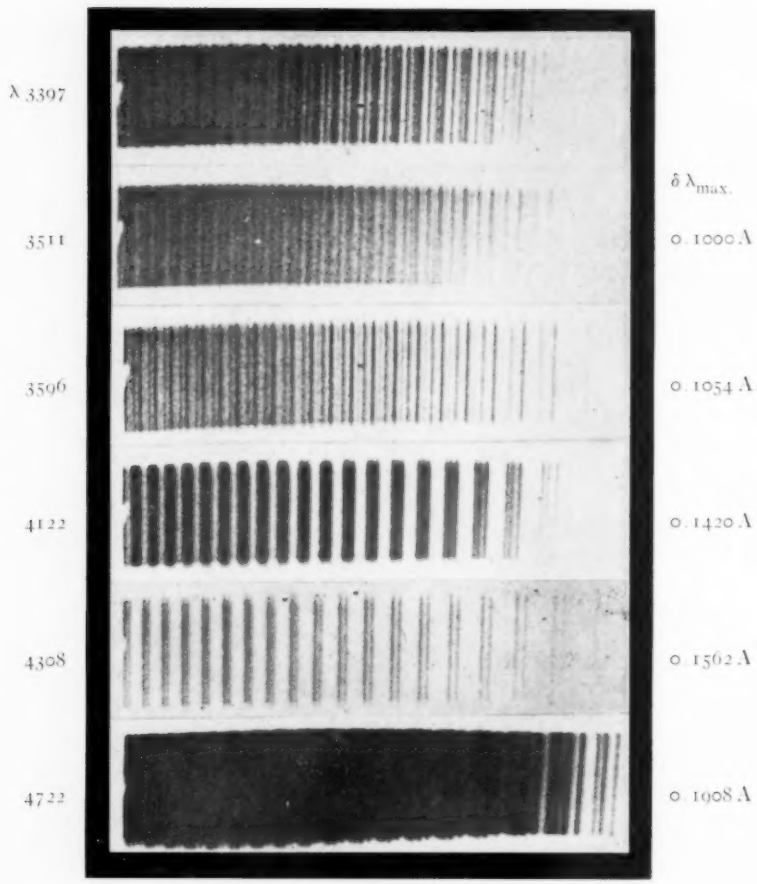
At the suggestion and under the guidance of Professor Nagaoka, the following experiment was made with the object of replacing the platinum foil of the cathode by a hard carbon strip. The carbon was previously soaked in a solution of calcium and barium nitrate, and dried; by using it as cathode, we can obtain electronic currents of several amperes per cm² in vacuum, and successfully

[1] *Annalen der Physik*, **29**, 833, 1909.
[2] *Dissertation*, Gottingen, 1912.
[3] *Jour. Coll. Sci.* (Tokyo), **8**, 51, 1915.
[4] *Astrophysical Journal*, **44**, 303, 1916.

apply this current for spectroscopic use. As a cathode, we cut a thin carbon strip from a telephone diaphragm in rectangular shape, 3×12 mm. The strip was heated red hot, and after cooling dipped in a solution of calcium and barium nitrate; before using, it was dried in a gas flame. Its ends were held by small steel clamps. Acheson graphite was pasted on the plate to make sure of good contact at the clamps. The strip was heated by an alternating current, which was led in by steel wires, sheathed in glass tubes. Currents of 8 to 16 amperes were used to heat the strip red hot, and on applying sufficient voltage between the anode and the cathode, the electronic current was established between them. Usually the heating current was taken off after reaching this stage, and no heating was necessary to maintain the current. The voltage between the electrodes was about 200 volts, but when the electronic current of several amperes was established it dropped to 30 or 40 volts. This potential difference was generally determined by the nature of the anode.

The life of the carbon strip depends on the pressure of gas in the vessel in which it is placed, the amount of the oxides coated on it, the amount of the heating current sufficient to cause emission of electrons to vaporize the metal of the anode, and the strength of the electronic current. It was necessary to keep the electrodes near each other and vaporize the metal. For Cd, Pb, and Bi, the distance was about 1 cm when the potential difference between the electrodes was about 200 volts. After 20 or 30 minutes, the carbon strip became gradually porous and broke down; but generally the anode metal was all vaporized before the carbon fell to pieces. The life of the strip was longer, the harder the carbon; generally initial over-heating was unfavorable, but when metallized with the anode material, the life was much longer. The metal was molten in a silica tube of about 2 mm internal diameter, and came in contact with the end of an iron lead-wire. With metals of high melting-point, such as copper, iron or tungsten, wires of these metals were taken. For examining salts, it was necessary to have a thin wire of a conducting substance passing through the salt. For studying powders of molybdenum or iodine, the powders were pressed into a silica tube. It was found advantageous to use different sizes of silica tube for different sub-

PLATE VI



SATELLITES OF LINES OF BISMUTH

stances. The anodes and cathodes sketched above were placed in a brass tube of about 4 cm internal diameter and 27 cm long, and provided with a silica plate cover, while the other end was closed by an ebonite plug, through which the electrodes were led. Owing to excessive heating, the tube was water-jacketed and the interior of the tube protected by inserting a thin mica cylinder. The tube was evacuated by a Gaede mercury pump, and the pressure maintained nearly constant during the experiment and kept much below 1 mm of mercury. It was afterward found advantageous to use a shorter but wider tube, with which lines of bismuth were studied. On increasing the heating current, the carbon strip was surrounded by a glow, and bright spots appeared at the anode which gradually spread over the whole surface of the silica tube exposed to cathode bombardment.

The intensity of the light depends on the current. The surface of carbon cathode emits a continuous spectrum interspaced with bands, but they do not interfere with the spectroscopic investigation, as the light from the anode only is focused on the slit of the spectroscope. The anode light is very intense, so that satellites of the bismuth line λ 4722 can be distinctly photographed by an echelon grating with exposure of 30 seconds only. With metals of low melting-point, the potential difference of 200 volts is sufficient to bring out good results, but with iron and other refractory substances, it is necessary to use higher voltages.

A glance at Plate VI will show how distinctly the satellites of the bismuth lines $\lambda\lambda$ 4722, 4308, 4122, 3596, 3511, 3397 can be photographed, by means of a quartz Lummer-Gehrcke plate and spectrograph of the same material by using the extraordinary ray. All the lines were taken on a single plate with an exposure of 5 minutes. The lines are not measured, as the orders of spectra of the satellites are not definite with a single plate; only with crossed spectra can we determine the orders.

We have to thank Mr. T. Mishima, assistant in the Institute of Physical and Chemical Research, for his kind assistance during the progress of the present work.

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July 1920

A MODIFICATION OF THE ELECTRON THEORY OF DISPERSION, TO ACCOUNT FOR THE CHANGE OF REFRACTIVE INDEX WITH TEMPERATURE

ABSTRACT

Electron theory of dispersion.—Attention is called to the fact that W. Voigt was the first to modify the Lorentz theory in such a way as to explain the *change of refractive index with temperature.*

Under the foregoing title Mr. Hulburt published in this *Journal*[1] an article in which he modified the Lorentz electron theory, in order to explain the decrease of the refractive index with increasing temperature.

Exactly the same modification of the electron theory was developed for the same purpose by the late Professor W. Voigt in his paper, "Contributions to the Electron Theory of Light," published in the year 1901.[2]

Voigt starts from the equation of motion of the dispersion electron in the well-known form

$$m_s\frac{d^2\xi}{dt^2}+k_s\frac{d\xi}{dt}+f_s\xi=e_sE_x$$

(where the subscript s denotes the sth type of electron) and he assumed that the quantities k_s and f_s are changed by the influence of a thermal or mechanical deformation.

In case of the deformation being caused by the change of temperature, Voigt showed that the refractive index μ of transparent isotropic media is expressed by

$$\mu^2-1=\sum_s\frac{4\pi N_s(1-\Delta)\frac{e_s^2}{m_s}}{\frac{k_s}{m_s}(1+b_s\Delta)-\frac{4\pi^2c^2}{\lambda^2}},$$

where N_s is the number of electrons of the sth type per unit volume, λ the wave-length of vibration, c the velocity of light in vacuo and Δ the dilatation produced by the change of temperature; the sum is to be extended to all types of electrons of the medium.

[1] *Astrophysical Journal*, **51**, 223, 1920.

[2] *Annalen der Physik* (4), **6**, 459, 1901.

This formula corresponds to equation 6 of Mr. Hulburt's paper; his remark that no previous attempt has been made to explain quantitatively the change of the refractive index with temperature, on the basis of the electron theory of dispersion, is therefore erroneous.

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MÜNSTER i/W.
November 1920

ON THE PRESSURE IN THE ATMOSPHERES OF THE STARS

ABSTRACT

Pressure in the atmospheres of Arcturus and Procyon.—A comparison of radial-velocity measurements of lines known to show large pressure-shifts with those of other lines seems to indicate pressures of, respectively, about 3 and 2 times that of the sun in the atmospheres of these two stars. However, it is not certain that the small positive shifts observed are due to pressure.

Permit me to call attention to the measures of the pressure in the atmospheres of the stars from observations of the displacements of the lines of the classes *a*, *b*, *c*, *d*, of Gale and Adams.[1] I should be interested to know if my results are confirmed with the more powerful instruments in America. With the use of Hartmann's spectrocomparator, I have compared the spectrum of Arcturus and of Procyon with that of the sun on plates obtained with the spectrograph arranged by M. Hamy in connection with the equatorial coudé. The scale of these spectrograms is 1 mm = 4A at λ 4300.

The difference in radial velocity was first determined from reference to the arc lines and from reference to the enhanced lines. When those lines only were used which appeared sufficiently isolated in Rowland's map, the difference in displacement was found to be +0.2 km/sec. for Arcturus, and +0.5 km/sec. for Procyon. This is in good agreement with the values of 0.08 and 0.58 km/sec., respectively, found by W. S. Adams[2] with a more powerful instrument.

Afterward I determined the difference between the radial velocity of the star obtained (*1*) with the lines of classes *a* and *b*, and the

[1] *Astrophysical Journal*, **35**, 31, 1912. [2] *Ibid.*, **33**, 67, 1911.

radial velocity obtained (*2*) with the iron lines of class *c* and with those lines of titanium shifting strongly under pressure. The result was +0.7 km/sec. for Arcturus, and +0.3 for Procyon, which would correspond to an average displacement of 0.010 A for Arcturus and 0.004 A for Procyon at λ 4400. If these displacements are due to pressure, it would be inferred that the pressure in the atmosphere of Arcturus is three atmospheres greater than that in the sun, while that in the atmosphere of Procyon would not exceed that of the sun by more than one or two atmospheres.

In the region between λ 4200 and λ 4700, I was able to measure only one line of class *d*, namely 4233.61 (Fe). Compared with the mean from all the other lines, the displacement of this line would be +0.006 A for Arcturus and only +0.004 A for Procyon.

If these results shall be confirmed by observations with more powerful instruments, they will tend to prove that the pressures in the atmospheres of the stars are very slightly greater than that of the sun, until type F inclusive is reached. The slight displacement of the line of class *d* would even suggest that the small displacements observed are not due to pressure.

P. SALET

OBSERVATOIRE DE PARIS
February 9, 1921